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OCEANOGRAPHIC SURVEY OF THE GULF OF MEXICO

Office of Naval Research
Contract N7 onr-48702
Navy Department

Project NR 083 036
Technical Report No. 12
April 1954

On the Circulation and Tidal Flushing of Mobile Bay, Alabama, Part I

George B. Austin, Jr.

Research Conducted through the

Texas A.&M. Research Foundation

COLLEGE STATION, TEXAS

THE AGRICULTURAL AND MECHANICAL COLLEGE OF TEXAS
Department of Oceanography
College Station, Texas

Research conducted through the
Texas A & M Research Foundation

Project 24

ON THE CIRCULATION AND TIDAL FLUSHING OF MOBILE BAY, ALABAMA, PART I

by

George B. Austin

April 1954

Reference 54-20T

Project 24 is an Oceanographic Survey of the Gulf of Mexico sponsored by the Office of Naval Research (Project NR 083 036, Contract N7onr-487 T.O. II). The work reported herein is of a preliminary nature and the results are not necessarily in final form.

Dale F. Leipper
Project Supervisor

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LIST OF SYMBOLS

ζ	Average tidal displacement
λ	$\frac{X}{L}$ = a dimensionless length ratio
ξ	Tide height
ρ	Density of water
σ	30‰ = Mean Gulf salinity
σ_t	Anomaly of density $\sigma_t = 1000\ (\rho - 1)$
ω	Angular frequency of the tide
a	River flow velocity
B	A dimensionless number, factor of proportionality in the eddy coefficient
BT	Bathythermograph, temperature-depth recorder
C	$100\ \frac{(1-S)}{\sigma}$ % or per cent of fresh water concentration at a point.
C'	$\frac{1}{z}\int_{-z}^{0} c\,dz$ per cent of fresh water
cfs	Cubic feet per second
D	River discharge in ft/min.
d	Average depth of segment (n)
F	$\frac{aH^2}{2B\,\xi_0^2\,\omega\,L}$ = Flushing Number
f	The fraction of fresh water in a mixture of fresh and salt water leaving a volume segment (n)
fwc	Fresh water concentration
H	Depth of estuary (a constant)
h	Depth of the mixed layer
L	Length of estuary (a constant)
M^3	Cubic meters

LIST OF SYMBOLS (cont'd)

P_n	Local tidal prism of segment (n)
Q_n	$\frac{R}{r}$ = Accumulation of river water
R	Volume of river water per tidal cycle
r_n	$r_n = \frac{P_n}{P_n + V_n}$ = Exchange ratio for segment (n)
r'_n	$\frac{P_n}{P_n + V_n} \cdot \frac{d}{h}$ = Modified exchange ratio
S	Salinity ‰
$\frac{S}{\sigma}$	A dimensionless salinity ratio
T-S	Temperature-Salinity diagram
t	Time
u	Tidal current
V_e	$\frac{R}{f}$ = Escaping volume
V_n	Low tide volume of segment (n)
w	Width of estuary (a constant)
x	Cartesian coordinate expression of length logitudinally down the axis of the estuary
y	Cartesian coordinate expression used for depth also (two dimensions)
z	Cartesian coordinate expression in the direction of depth but positive upwards

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ON THE CIRCULATION AND TIDAL FLUSHING OF MOBILE BAY, ALABAMA, PART I

George B. Austin

Abstract

A description of the results gleaned from a hydrographic survey of Mobile Bay, Alabama is presented. A brief oceanographic description of this bay is made also, from the standpoint of the five phases of Oceanography as defined by D. F. Leipper (1950). The presentation and discussion of the distribution of temperature, chlorinity and fresh or river water, and a description of the currents observed constitute the greater portion of this paper.

The author evaluates two ideas or methods of estuarine flushing determination offered by B. H. Ketchum (1950) and H. Stommel (1951) as they apply to Mobile Bay. The observed distributions and variations in chlorinity as affected by tidal changes were used for a control in the above investigation. A flushing time for this estuary for the period of the survey (October, 1952) was found to be fifty days.

ON THE CIRCULATION AND TIDAL FLUSHING

OF MOBILE BAY, ALABAMA

I. INTRODUCTION

A. Historical

Until recent years emphasis in the field of physical oceanography has been directed toward the study of the structure and circulation of the deep oceans. The study of estuarine problems did not become a recognized phase of physical oceanography until the turn of the century, and then the major endeavor was centered in Europe (i.e. Norway, England). It was not until very recently, the last ten years, that any noteworthy or concerted effort was made on this continent into the study of estuaries. Sanitary engineers have had to deal with a problem of sewage disposal in small bays and harbors for some time, but it was not until the end of World War II that an appreciable interest was displayed by the oceanographer in the study of physical problems associated with the shallow coastal regions of the oceans. Following World War II, the problem of industrial pollution of bays and harbors and the possibility of future atomic bomb attacks on our coastal cities precipitated an interest of an oceanographic nature in the dynamics, circulation and flushing of our bays and harbors.

Physical concepts which had been applied with reasonable success to the deep oceans were found to have only a few applications to the estuarine problem. Assumptions which held true in establishing boundary conditions for the deep oceans no longer held true for the smaller, shallow estuaries. Today many apparently basic questions concerning estuarine dynamics remain to be answered satisfactorily. The problem is complicated due to the fact that each estuary is unique in itself, and a satisfactory explanation of the dynamics of one estuary may not come close to an explanation of the dynamics of any other estuary.

In 1949, Tully, J. P. (27) published the results of an extensive hydrographic investigation of Alberni Inlet, Canada, in which he attempted to establish a workable method for the prediction of pulp mill pollution in Alberni Inlet. How well he succeeded has yet to be determined, because of the complexities of the problem of estuarine circulation. It is of interest to note, however, that Tully has received much acclaim for his work, and the procedures and techniques which were used by him have been applied rather extensively to similar situations of estuarine study elsewhere.

In 1950, Ketchum, B. H. (10) published the first of several papers associated with the circulation and flushing of tidal estuaries (Raritan Bay). One of these, "The Exchange of Fresh and Salt Waters in Tidal Estuaries" (1951) (8) describes his modified tidal prism theory, which will be applied in the investigation here. An attempt to evaluate Ketchum's theory as applied to Mobile Bay is presented.

A number of other investigations of the physical oceanography of estuaries have been carried out in the past few years. These include studies by Pritchard, D. W., Chesapeake Bay, 1952, (15); Stommel, H., 1951, (22); Arons, A. B., 1951, (21); Farmer, H. G., 1951, (6); Cameron, W. M., Chatham Sound, 1951, (2); Trites, R. W., Chatham Sound, 1951, (26); and many others.

B. Classification of Estuaries

Pritchard, D. W., 1952, (16) in his chapter on Estuarine Hydrography has carefully summarized the classification of estuaries into several types based on different physical factors. One such classification is made on the basis of fresh water inflow and evaporation. From this classification there are three possible subdivisions, positive, inverse and neutral estuaries. The positive estuary is one in which river runoff and precipitation together exceed evaporation. The inverse estuary is one in which the evaporation exceeds the river runoff and precipitation, and is often termed a lagoon. The neutral estuary presents a balance between river runoff, precipitation and evaporation in which none of these factors predominate.

A second type of classification of estuaries is in terms of the geomorphological structure. Of this class, the coastal plain estuary predominates from the standpoint of present day emphasis of study. These estuaries have been formed by the drowning of former river valleys or deltas, either by subsidence of the land or a rise in sea level. Mobile Bay is of this type. Other subtypes under this classification are (1) deep-basin type or fjords, (2) bar-built, very shallow type or lagoons.

Pritchard defines an estuary as a semi-enclosed coastal body of water having a free connection with the open sea and containing a measurable quantity of sea salt. Ketchum in his work gives a broader definition which is objectionable only in its broadness. He states that an estuary is any region in which sea water is measurably diluted by land water drainage. Mobile Bay fits both of the definitions for estuaries presented by Pritchard and Ketchum and may be further qualified geomorphologically. The physical causes of the movement and mixing of water in the estuary, whether tidal, meteorological, or by river flow, further classify the estuary according to Stommel, H., 1951, (22).

Thus from the definitions and classifications described above, one can say that Mobile Bay is a positive coastal plain estuary of the northeastern Gulf coast which undergoes effective changes in its patterns of movement and mixing due to meteorological and river runoff changes.

C. Objectives.

One of the principal objectives of this treatise is to measure and describe the distribution of temperature, salinity and currents of Mobile Bay, Alabama. Another objective is to evaluate the flushing time for this estuary using data which were collected on a hydrographic survey in October, 1952, and B. H. Ketchum's Modified Tidal Prism Theory, 1951 (8).

Mobile Bay presents a particularly challenging problem because of the paucity of information available for this particular estuary. The U. S. Coast and Geodetic Survey (29,30) has conducted tidal measurements of height and current for a few selected points within the bay, but they have not attempted to describe circulation within the bay, flushing time for the bay, or the non-tidal currents and drift within the bay.

In 1895, Ritter (18) made the first recorded survey of the extent and condition of the oyster reefs in Alabama waters. His description and map of Mobile Bay contained extensive salinity and depth data for all regions of the bay in which oysters were observed to be.

J. O. Bell, 1952, (1) conducted a survey of the oyster production in Mobile Bay and surrounding waters in which he collected temperature and salinity data for a number of points. Bell made no attempt, however, to explain the circulation or flushing time for the bay.

To the knowledge of the author the flushing time has not previously been determined for Mobile Bay; therefore, it will, in itself, be a significant contribution to present or future studies which may be undertaken in this region (e.g. the pollution study of Mobile Bay is now in progress by the Alabama Department of Health).

II. GENERAL DISCUSSION OF MOBILE BAY

A. Geomorphological.

Mobile Bay (Figure X) has an overall area of approximately 297.18 square miles (nautical), averages 9.81 feet in depth at mean low water and attains a maximum depth of 60 feet off Fort Morgan near the main Gulf entrance to the bay. The bay is 27 nautical miles in length, 19.8 nautical miles at its widest point and averages 11 miles in width over its entire length. The shape of the bay is roughly that of a boot with the toe pointing toward the east.

The major or longitudinal axis of the bay runs north and south. To the north several rivers empty into the bay. These include the Mobile, Raft, Tensaw, Appalachee and Blakeley Rivers. Of these, the Mobile and

Tensaw Rivers are the dominant contributors of water and sediment to the bay. In turn, all of the rivers described are distributaries of the confluence of the Alabama and Tombigbee Rivers located approximately forty-four miles upstream from Mobile..

To the south the bay has two major outlets to the sea (Figure X). One, the southernmost or Main Pass, empties directly into the Gulf of Mexico and handles approximately 3/4 of the total volume of water which is flushed into or out of Mobile Bay. The second opening, which is located in the southwest corner of the bay, empties into the Mississippi Sound and flushes most of the remaining 1/4 of the total volume of water which is transported into or out of the bay.

The southwest opening, or Pass Aux Herons as it is known, is 2.15 nautical miles in width and has an average depth of 3.3 feet with a maximum depth of 15 feet in the intercoastal waterway channel. The south pass, or main pass into Mobile Bay, is 2.78 nautical miles in width with an average depth of 16.3 feet and a maximum depth of 60 feet off Mobile Point. Several small streams and/or bayous enter the bay on both sides, but they contribute only 5% (approximately) of the total river run-off, according to the U. S. Corps of Engineers (28) at Mobile.

The bottom topography of the bay is fairly flat with few irregularities other than the dredged ship channel (32 feet deep) and consequent spoil area paralleling the ship channel over its entire length. The bottom slopes gradually and evenly from the sides or boundaries with two principal exceptions: (1) at the ship channel and (2) at the main pass into the bay. As mentioned earlier, there are several active oyster beds scattered over much of the lower half of the bay and also a number of dead shell reefs buried in the upper bay. It is possible that such reefs may add considerably to the roughness characteristics of the bottom.

The mean range of tides for the bay is 1.5 feet. The maximum range that could be expected from anomalous meteorological effects is on the order of six to eight feet. The tidal waves resulting from hurricanes, which occur not infrequently (eleven year cycle approximately), could be on the order of fifteen feet in height.

B. Geological:

Carlston, C. W., 1950, (3) describes the submerged valley of Mobile Bay as follows: "The bottom of Mobile Bay is quite flat. Soundings by the U. S. Coast and Geodetic Survey show an average depth of ten to eleven feet below mean low water. Opposite the mouth of the bay and the western tip of Mobile Point is a submerged arcuate delta, which has a base about ten miles wide and extends four miles out into the Gulf. Because the top of this submerged delta is also about ten to eleven feet below mean low water, it is evident that it is a delta of Mobile River and of the same age as the submerged valley of the river.

These features indicate that the most recent event in the Pleistocene history of coastal Alabama was the submergence up to the present sea level of a river valley and delta formed during post-Wisconsin time. This recent rise in sea level was ten to eleven feet."

An attempt was made to correlate the mean width to maximum depth in Mobile Bay after a method applied to round and oval bays in Louisiana and Texas by Price, W. A., 1947, (13), but no success was realised due probably to the ratio between "maximum length to greatest perpendicular width" being in excess of the limiting ratio of Price's study (1:3.25). Another factor which would distort the "Average diameter: maximum depth" ratio is the presence of bodies of spoil along the Mobile Ship Channel. This spoil in effect divides the bay longitudinally into two basins, approximately doubling the "length to width" ratio. Price's method gives an excessive depth for this bay. It is evident that equilibrium conditions for this bay are unlike those of the round and oval bays to the west.

No investigation was made concerning quantitative effects of sedimentation and/or erosion in Mobile Bay. It has been observed in the literature (3), however, and from personal observation over a period of twenty years that the shore lines of the bay are being eroded away due to wave action at a rate of approximately 0.5 ft. per year. The resulting sediment is being carried out of the lower bay at a rate to maintain a fairly constant water depth. However, there is much evidence that active silting and sedimentation is taking place in the upper reaches of the bay.

The U. S. Corps of Engineers maintains the Mobile Ship Channel to a depth of thirty-two feet. Dredging operations proceed during most of the year since this depth is some twenty-two feet below the mean bay depth and the channel tends to fill rather rapidly. The spoils of dredging are pumped to either or both sides of the ship channel, but more often to the western side. As a result spoil areas have built up to within three or four feet of the mean low tide water level in many places.

The bottom of the bay is composed to varying degrees of soft sediments, mud, clay, in many places old shell reefs (oyster) now dead, a few active reefs on the eastern side of the bay, and in the shallower water, sand.

C. Biological.

As is true of most estuaries, Mobile Bay offers a suitable environment for the growth and production of seafood. A shallow marine habitat, abounding in nutrients from the land (river run-off) and from the sea (Gulf of Mexico) offers a wide and varied opportunity for the production of plant and animal life requiring vastly different environments from that of fresh water to that of sea water.

Commercial oyster and shrimp industries prevail seasonally. Sport fishing is prevalent the year round and abounds from early spring to late fall. Commercial fishing in the area is also quite extensively practiced.

A note of biological interest is the seemingly periodic occurrence of the seafood "jubilee" which is unique to this estuary and is evidenced by the large migration of certain fishes and other forms (flounders, mullet, sting rays, crabs) to the eastern shore of the bay every few years. No completely satisfactory explanation has yet been offered for the cause of this phenomenon (although many speculations have been made by both laymen and marine biologists).

The Alabama Department of Health, in conjunction with the Department of Conservation, has conducted a continuous survey on pollution in the bay since shortly after the end of World War II. It was found that, during periods of high river run-off, the lower bay (oyster producing region) is polluted with coliform bacteria. As a result, commercial tonging in the area is restricted or regulated until such a time as pollution is effectively reduced.

Good oyster production in Mobile Bay proper has been maintained in recent years through an intensive program of seeding and shelling, and, probably more important, the restriction to tonging (no dredging) which has been carefully enforced. Causes of periodic mortalities appear to be natural, disease and marine predators being the most common in evidence. Some sources attribute the primary cause of the high mortalities among oysters to heavy pollution, but little or no direct evidence has been found to confirm this belief.

D. Chemical.

The distribution of chlorinity (vis. salinity) in Mobile Bay served to aid as a "tracer" of the "fresh" river water concentration (fwc) in the bay. No effort was made during the October survey to determine the distribution or concentration of any other chemical constituent. Usually an important feature of a survey of bay waters is to determine the distribution of one or more of the chemical constituents present. Probably most frequently analyses of the water for pH (function of acidity), phosphate, oxygen and total dissolved organic materials are made, however, other chemical data are collected as the need arises.

Increased problems of industrial (chemical) pollution and raw sewage in many bays and harbors precipitated a need for a more complete analysis and evaluation of the mixing processes, flushing rates and the circulation of estuaries (i.e. Raritan Bay, Alberni Inlet, San Diego Harbor, San Francisco Bay, Puget Sound and Tampa Bay).

An aspect which should be considered is the meaning of the terms chlorinity and salinity, and their limitations when applied to an estuarine situation. Sverdrup, et al, 1946, (25) wrote: "The number giving the chlorinity in grams per kilogram of a sea water sample is identical with the number giving the mass in grams of "atomic weight silver" just necessary to precipitate the halogens in 0.3285233 kilogram of the sea water sample" and salinity is defined as, "the total amount of solid material in grams contained in one kilogram of sea water when all the carbonate has been converted to oxide, the bromine and iodine replaced by chlorine, and all organic matter completely oxidized." An empirical relation exists between chlorinity and salinity which is expressed as follows:

$$\text{Salinity} = 0.03 + 1.805 \times \text{Chlorinity} \qquad (25)$$

The definitions above were based on a physical property of open sea water which is "Regardless of the absolute concentration, the relative proportions of the different major constituents are virtually constant, <u>except</u> in regions of high dilution (low salinity) where minor deviations may occur." (25)

It is apparent then, that in an estuary (usually a region of high sea water dilution) the term salinity should not be defined as above and still indicate accurately the total salts. The relative proportions of the different major constituents do vary somewhat, and from estuary to estuary.

For this study no change in the definition of salinity has been made; therefore, the term salinity is used to define the chemical properties of estuarine water in the same sense and meaning as this term is used to define the chemical properties of sea water. The assumption that is made is that the chemical constituents of estuarine waters remain in the same relative proportions as they are found in sea water. Inasmuch as salinity is used here as a "tracer" for fresh water concentration (fwc) only, finer shades in the true meaning of the term is not to be considered important.

E. <u>Meteorological.</u>

The extent to which the weather (i.e. atmospheric temperature, pressure, precipitation, evaporation and wind) affects the dynamics of an estuary is not completely unknown, but much remains to be done in this field. It is known that winds can produce water level changes which very significantly alter the water level associated with the ordinary astronomical tides. Sudden and marked changes in atmospheric pressure also tend to alter predicted tide levels to some degree.

A good example of the effects of a sudden wind change is best illustrated in Figure No. 1, which shows two tide gage or water level recordings which were taken simultaneously at different stations. Record No. 1 was taken in the Mobile River at the city of Mobile, and Record No. 2 was taken at Cedar Point near the mouth of the estuary. After a short period of fair weather (low wind velocities from the south and west), a "norther" blew in on the 28th of October bringing lower temperatures and strong northeast winds. This situation lasted for two days, and the effects on the water movements in the bay are rather clearly demonstrated in the tide records. The ebb stage low water level in Mobile River decreased to approximately one foot below its normal low level, and at the Gulf end of the estuary during the ebb stage it is observed that a piling up of water above the expected low tide level takes place during the same normal ebb period.

These meteorological factors contribute much to the complexities observed in the mixing and movement of water in an estuary, and these complexities make it very difficult for the oceanographer to formulate a satisfactory method for predicting the circulation and/or flushing in any estuary. According to Collier, A. S., 1950, (4), the so called meteorological tides have a far greater effect in the mixing processes of certain lagoonal type estuaries (i.e. Laguna Madre) than the astronomical tides, because of the small range of astronomical tide changes normally observed in a lagoon. By definition a lagoon may have a very small or even no opening to the adjacent sea. (16)

The effects of precipitation and evaporation are important enough to offer one method in the classification of estuaries (Introduction). This classification depends on whether precipitation or evaporation predominates, or whether neither factor dominates.

An estimate of evaporation from the bay for this region in October of the year is taken from Jacobs, 1951, (7), and amounts to $5.0 \times 10^6 M^3$ per day or approximately 1/5 of the volume of river run-off per day for October, 1952. This value for evaporation is equivalent to 0.16% of the total mean volume of water computed to be in Mobile Bay at the high tide.

Although the annual mean rainfall for the Mobile area is sixty-five inches per year, no precipitation was recorded for the area during the period of survey and the month preceding it. In fact, the survey was made immediately following one of the Southeast's driest summer and fall seasons in a decade. Effects of this drouth are noticed in the low volume of river flow recorded for this period (10,000 cfs or less).

III. TIDAL FLUSHING THEORY

A. Ketchum's Tidal Prism Theory.

In essence an empirical theory which describes the exchanges across various selected cross-sections, Ketchum's theory permits the calculation of the mean distribution of fresh and salt water in an estuary (9). The theory further implies, therefore, the exchanges of other properties of the water such as contaminants, nutrients, etc. Simplicity in application is one primary advantage of the method (10).

An estuary is defined by Ketchum as a region where river water mixes with and measurably dilutes sea water. An assumption that a steady state condition exists as to the daily mean distribution of fresh and salt water is necessary. This is evidently true for long periods of time (since estuaries are not becoming either more fresh or more salty with time). However, it is acknowledged that this may not be true for short time intervals. The changing rate of river out-flow would be a major factor in changing the salinity of an estuary.

Therefore, two conditions must be met in order to maintain a steady state distribution of fresh and salt water at every cross-section of an estuary. There must be no net exchange of salt during a tidal cycle across a section, and there must move seaward a fresh water volume equal to the volume introduced by the rivers in the same time interval, neglecting evaporation.

Ketchum defines a dynamic boundary at the inner end of the estuary as the section above which the volume required to raise the water level from low to high tide is equivalent to the volume of water contributed by the river during a tidal cycle. The segment is placed in such a position that the water above it remains fresh at all tides. At the ebbing tide this section will lose one river flow volume per tide. The seaward boundary marking the "0" volume segment will, of course, move depending on the rate of river flow experienced. Since all other seaward volume segments and their boundary cross-sections are dependent on the selection of Segment "0" and its seaward boundary, it is important that a careful choice be made for Segment "0".

Segment "0", discussed above, marks the inner boundary of the estuary and also defines the initial volume segment. The next seaward volume segment is defined as that volume segment of water at low tide equal to the inner or landward high tide volume segment. This process is repeated seaward until the seaward boundary of the estuary is reached.

The distance between the inner and outer boundaries of volume segments so defined becomes in effect the average excursion length of a water particle during the flooding tide in that section of the estuary. These average excursion lengths may thus be considered as a rough approximation of the mixing lengths for an estuary and according to the theory as presented by Ketchum this is in effect the manner in which they are used. Ketchum defines the tidal prism as the volume of water required to produce the observed rise in water level in an estuary as a result of the flooding tide, and the local tidal prism as the difference between mean low tide and mean high tide volumes in each segment of an estuary.

In defining an exchange ratio (r_n) Ketchum makes a rather broad assumption (to many minds) that the water within a volume segment defined as above is completely mixed at the high tide and that the proportion of this water removed by the ebb tide is given by the ratio between the local tidal prism and the high tide volume of that segment (n), or as an equation:

$$r_n = \frac{P_n}{P_n + V_n}$$

The assumption that complete mixing will occur in each volume segment is too easily disproved. Fairly good mixing can and does occur vertically in many estuaries, if not too deep (twenty feet or less), probably as a result of strong wind effects and tide flow over very rough shallow bottoms as much as due to any other cause. Lateral mixing, however, is another story. It has been observed in many estuaries that the intrusion of sea water will tend to be deflected to the right (facing upstream) in an estuary in the northern hemisphere which can be explained on the basis of the effect of the earth's rotation. Hence, on observation one finds high saline water to one side of Mobile Bay and fairly fresh river water to the other side. The greatest amount of horizontal mixing that will probably occur in such a situation appears to result from anomalous meteorological effects and tidal exchanges and not from internal diffusion and/or small turbulences derived from the normal or characteristic flow patterns inherent in the dynamics of the field, although these must certainly contribute to the overall mixing processes, but to a lesser degree.

Stommel, 1951, (22) demonstrates that in a two layer fluid system, the bottom or high salinity fluid, which is more dense, will tend to remain undisturbed by the low density fluid (fresh water) lying above. This is true unless some external force of considerable magnitude is applied, such as a wind at the surface or a strong tidal movement. Even then the two fluids do not attempt to flow or mix appreciably at their common boundary unless the interface becomes turbulent. The vertical mixing process which takes place appears to be restricted to one direction (up), with the more dense deep water mixing upward into the shallow less dense medium while little surface water appears to mix downward.

Tidal oscillations appear to have contributory effects in the mixing processes of an estuary. In fact, they may well be the greatest single factor which induces mixing between fresh and salt water in many estuaries. This could be especially true in estuaries exposed to strong semi-diurnal tides with extreme water level changes (five feet or greater) as one finds on our eastern seaboard (17). On the Gulf Coast, however, diurnal tides exist with water level changes which rarely exceed two feet in height and the mean appears to be on the order of 1.5 feet.

It is probably as a result of the smaller and less frequent tidal action which is observed on the northern Gulf coast estuaries that makes it difficult for one to explain which natural factor (tide, wind or river flow) contributes the most to the mixing processes.

It is, therefore, very interesting that Ketchum's tidal prism theory can apparently produce results for several estuaries (e.g. Raritan Bay, Alberni Inlet and Great Pond) which are of the same order of magnitude as the observed results of fresh water concentration.

For incomplete vertical mixing, which is readily detectible from the vertical salinity distribution, it is essential that only the upper or mixed layer volume of the column be considered. A modified exchange ratio (r'_n) is then applicable as follows:

$$r'_n = \frac{P_n}{P_n + V_n} \cdot \frac{d}{h}$$

where d is the average depth of segment (n) and h is the depth of the mixed layer. The ratio $\frac{d}{h}$ will increase the exchange ratio (r) and hence decrease the volume of fresh water accumulation (Q_n) for the segment (n). Such a modification of the theory in effect treats the water below the mixed layer as though it had no part in the tidal mixing process and that this water could be replaced by a false bottom without changing the distribution.

Incomplete horizontal mixing, discussed above, will also modify results from Ketchum's method. These effects are not incorporated into Ketchum's theory, as there seems to be no independent criterion which can be used to correct the exchange ratio for this condition. The discrepancies which do appear (Figure IV) between observed and calculated values of river water accumulation are probably due to incomplete horizontal mixing.

Ketchum defines the mean age of the river water as the average length of time required for the river water to move through a volume segment. The mean age of the river water or flushing time for the entire estuary is thus the sum of the mean ages of river water of all segments of the estuary.

The escaping volume, which is a mixture (after leaving segment "O") of salt water and fresh river water, is by definition the ratio of the river flow per tide (R) to the fraction of fresh water in the mixture (f), or

$$V_e = \frac{R}{f}$$

The ratio may be applied to estuaries in the calculations of escaping volumes from the salinity data of a hydrographic survey. The tidal prism theory defines a similar escaping volume as the intertidal local prism, in other words, the escaping volume for a section of the bay is the local tidal prism of the volume segment containing or bounding that section. This volume which contains a mixture of sea water and river water is removed on the next ebb tide and does not return through that section again according to the theory.

The escaping volume is important in the removal of pollution from an estuary as it provides the medium for dilution and removal of waste products. Since these local tidal prisms normally increase in size toward the mouth of an estuary, the concentration of the waste products is decreased as a result of increased dilution. It is of interest to note that the flushing of the inner end of the estuary is almost entirely dependent on river flow, whereas at the sea or outer end of the estuary tidal action is the predominant factor in flushing. In the estuary proper a combination of the two factors appears to be responsible for the flushing.

B. Stommel's and Arons' Mixing Length Theory of Tidal Flushing.

Shortly after Ketchum's Tidal Prism method was in print, Stommel and Arons presented a Mixing Length Theory of Tidal Flushing, 1951, (21) which was in effect a modification of Ketchum's work. The basic assumption that is made is the same one that Ketchum implied - that the mixing length is dependent on the flooding tide excursion length. Stommel and Arons attempted to translate this fundamental assumption into the language of physics of continua.

Other assumptions and boundary conditions which go to make up the theory include: reduction of the problem to a one dimensional case, an estuary of uniform width, depth, length and simultaneous variation in tidal height over the entire length of the estuary.

A non-dimensional flushing parameter (F) is derived from the theory and contains a proportionality factor(B), which proved to be characteristically indeterminant for several estuaries. It was of a different order of magnitude for the three estuaries tested (Figure XVIII). This implied that a calculated flushing number from the theory could not be used as an index of tidal flushing.

The theory was tested for Mobile Bay, but the results (Figure XVIII) indicate a wide variation in flushing numbers which indicate that for this one estuary the observed data fail to show even fair correspondence to any one of the family of curves of Figure XVIII. This fact further demonstrates the need for a more lucid understanding of the mixing, flushing and circulation of estuaries.

Figure XVIII was constructed from the two dimensionless quantities $\frac{s}{\sigma}$ and $\lambda = \frac{x}{L}$ on which were plotted curves representing various values of (F), the "flushing number" (Figure XVIII). It can be seen that observed data of Mobile Bay fail to fit a characteristic flushing number for any considerable length of the estuary, even though data from Raritan River and Alberni Inlet fit two of the (F) curves rather well.

IV. THE HYDROGRAPHIC SURVEY

A. Planning.

In September of 1952, tentative plans were initiated by the author for a hydrographic survey of Mobile Bay, Alabama. It was necessary to decide carefully what equipment would be needed, the number of personnel required, and, more important, an exacting time table necessary to obtain the most nearly synoptic situation possible with the available equipment and personnel.

Because of the distance involved (600 miles) from College Station, Texas to Mobile, Alabama, equipment and personnel for the survey were limited to what could be transported in one "carry-all". Mr. Walter Lang of the Department of Oceanography at Texas A. & M. College assisted the author in the survey. Equipment which was taken along included two shallow water bathythermographs for temperature-depth measurements; two surface buckets and Taylor thermometers for surface water temperatures; one sling psychrometer for wet and dry bulb air temperatures; one K.& E. hand operated anemometer; two magnetic compasses; one stop watch; one Price current meter; one Pritchard vane-type current meter (14), which was used for current directions only; one portable "A" frame and winch from which to handle the BT and Pritchard current meter; two sextants for positioning; two hundred feet of manila rope for use with the sampling devices; one salinity sampler; anchors; cord; floats and flags for eighteen station markers; data sheets; pencils; and a few hand tools.

Upon the decision of the author to use B. H. Ketchum's Tidal Prism Theory as the method of study for Mobile Bay, a preliminary investigation was carefully carried out. This included estimating the expected river run-off for October, 1952, the Mobile River-Bay volume relations and choice of volume segments and boundaries according to Ketchum's method (Figure X). A mean October river flow of 13,500 cfs was used (later discovered to be slightly too large), which was determined from a mean of fifteen years' October river flows for this region. Twenty-eight stations were chosen such that the boundaries between adjacent volume segments would be adequately surveyed. (See Figure X)

Of primary importance to the success of the survey was the cooperation and generosity of the Alabama Department of Conservation, which furnished laboratory-living facilities and two excellent survey boats.

B. Collection of Data.

Six work days were required to obtain the minimum amount of data necessary for this study. Two boats were used; one, a work boat, was excellent as a stable platform, but proved too slow for the survey which was being conducted. It was only possible to obtain approximately 1/3 of the planned bay stations per tide. However, it later became possible to use a fast speed boat for the last half of the survey, which enabled the survey party to cover 80% of the planned stations for the entire area during one tide.

Time-on-station was reduced to six minutes or less. This was enough time to take the necessary complete samples of temperature, water, currents, a sling psychrometer reading, wind speed and direction, and a BT. Running time between stations varied from ten to forty minutes depending on distance between stations and difficulties in locating markers, which had been placed during the initial station coverage.

Sixty-eight BT's were taken, over 250 water samples were collected for salinity determinations, and 170 current measurements were made. The Price current meter was used to measure the magnitude of current velocity and a Pritchard vane-type meter was used to measure the current direction (this meter had not been calibrated for speed prior to the survey). Care was taken to record properly on a standard form all data which was collected. A special effort was made on the part of all members of the survey party to curb or eliminate the human factor which so often tends to distort natural data (i.e. guessing direction or estimating time). Sampling methods were standardized and,where feasible, one individual had one or more functions as his sole responsibility for the duration of the survey.

The survey was begun on the 25th of October, 1952, and continued through the 31st of October, with one discontinuity which occurred on the 29th of October and forced the survey to a halt on that day. A strong "norther" was the cause of the interruption in survey operations.

An attempt was made to use direct reading salinity hydrometers for a quick means of salinity determination, but these proved unsatisfactory for ascertaining the small variations in salinity observed at some points in the bay. Bottle samples of water were then collected and brought back to the Department of Oceanography where chemical titrations for salinity were made using the Knudsen method (12).

V. ANALYSIS OF THE DATA

A. Methods

Upon the return to College Station from Mobile, Alabama, all recorded data were transposed from the field data sheets to more suitable forms for analyses, and checked. Chemical titrations for chlorinity of the water samples were begun. Meanwhile, BT slides were processed, read and recorded in temperature-depth tables. Current data were converted from the recorded meter readings to knots and transcribed in a suitable table. The chlorinity titrations occupied the better part of six weeks. These data were converted to salinity from Knudsen's Tables (12) and tabulated assuming that the chlorinity-salinity ratio of sea water is valid for an estuary.

For each of the twenty-eight station positions, curves were then drawn for temperature-depth and salinity-depth for the different observed tidal stages. From these curves temperature-depth sections (Figure V) and salinity-depth sections (Figures VI, VIa, VII) were constructed for six cross-sections of Mobile Bay and for the ship channel length, for the different tidal stages.

Current velocity vectors were plotted by station for surface and bottom at ebb and flood tidal stages. From these data surface streamlines of velocity (directional only) were drawn for both tide phases. (Figures XVI, XVII)

B. Distribution of Temperature, Salinity, and Fresh Water.

Next the horizontal distribution of temperature (isotherms) were drawn for two levels, surface and five ft. depth, but only the surface pattern of temperature at ebb and flood tides is presented (Figure XI). It appeared from the data that the horizontal distribution of temperature in Mobile Bay followed no presently useful pattern (true of many estuaries (15)). The temperature at the surface was for all practical purposes constant (two degree variation), and seemed dependent on the air temperature more than any other one factor. The vertical distribution displayed an inversion (Figure VIII) warmer bottom (Gulf) water below colder surface waters. In a few situations the temperature was observed to be constant from surface to bottom. The tidal variation appeared to have little effect on the temperature variation and distribution, possibly due to its long period (twenty-four hours) of oscillation.

The distribution of salinity (isohalines) has been emphasized since salinity is the medium by which flushing is computed and circulation is inferred. Surface, five feet and ten feet isohalines have been constructed from the salinity-depth sections (above) for ebb and flood tidal variations (Figures XII, XIII, XIV).

It was observed that tidal fluctuations bring about marked changes in the distribution of salinity, horizontally and vertically in the bay with probable emphasis on the horizontal variation. As appears to be true with most estuaries (16), the distinctive right-hand-side intrusion (facing upstream in the northern hemisphere) of the sea water was a predominant feature of the salinity distribution in Mobile Bay.

Pritchard (15) satisfactorily explains this in terms of the effect of Coriolis force for the Chesapeake Bay system. In Mobile Bay, however, there is an added feature of interest which might be considered for a more complete explanation of the observed salinity distribution. The spoil area paralleling the ship channel for its greatest length is built up on the left or western bank of the channel to within four and five feet of the water surface in many places and thus presents a physical barrier to the flow of the more dense saline Gulf water over this "fence" and into the western reaches of the bay.

A definite two layer system was in evidence during the October survey over most of the bay area, particularly in the region of the ship channel and to the eastern reaches of the bay. In the shallower regions (eight feet or less) and to the western side of the estuary the water was homogeneous in nature, indicative of thorough mixing to the bottom.

An intense salinity gradient was observed at or near the thermocline, which varied from three to ten or twelve feet in depth depending on the tidal phase, day of observation, location and weather. Eight to ten feet on the average appears to define the mixed layer depth for the bay, and this depth (ten feet) is used in the flushing analysis.

The U. S. Corps of Engineers (28) contend as a result of a two year salt wedge study of the Mobile River, that tidal oscillations appear to have few permanent effects on the penetration of the salt water wedge up the Mobile River. The amount of penetration of the wedge upstream is a result of the amount and/or rate of river flow (higher rates of flow - 50,000 cfs- have been observed to force the wedge out of the river). For low river flows (10,000 cfs) evidence of the wedge has been observed twenty-three miles upstream in the Mobile River from the city of Mobile. However, from recent time-distance studies of the salt wedge in Mobile River it is evident that tidal oscillations produce short period oscillations of the salt wedge-river water boundary in Mobile River.

The per cent of fresh water concentration (% fwc) is determined for the bay at the ebb and flood tide stages (Figure III). The vertical distribution of salinity was used as the indicator, and it was necessary to assume a value of mean Gulf salinity as the salinity value available for the flushing of the estuary. The value chosen initially was 34‰ which appears to be excessive for several possible reasons. The use of this value gives exaggerated values of fresh water accumulation in the bay. It was found that although measured Gulf salinities at the late flood tide at the main pass equal or exceed the value 34‰ salinity, 1/4 to 1/3 of the total flushing volume enters Mobile Bay through Pass Aux Herons (southwestern pass) with salinities which rarely exceed 28-29‰. Therefore, the use of a more conservative value of salinity was made in the % fwc determination (30‰).

The relation which is used in the determination of % fresh water concentration is

$$C = 100 \left(\frac{1-s}{\sigma}\right) \%$$

where S‰ is the observed salinity at a point and σ is the value chosen as the mean available flushing salinity. In order to determine the C (% fwc) for a discrete volume it is necessary to integrate from the surface to the depth of measurement (i.e. ten feet) as follows:

$$C' = \frac{1}{z} \int_{-z}^{o} c\,dz \qquad \text{(positive (z) upward)}$$

where C' is the concentration of fresh water and (z) is the depth. A mean value of C' is thus determined for the depth. Several C' determinations over an area when properly contoured allow an integration which will give a mean value of fresh water concentration for any volume segment under consideration.

Contours or isolines of C (% fwc) are given for ebb and flood tide stages. It is interesting to note the degree to which this type of presentation has a "smoothing out" effect on the salinity distribution (Figure XV) in that it is a measure of salinity over a finite depth and absorbs the complexities of tongues and/or pockets of salinity. Mean per cents of C for intervals of one nautical mile were determined from the salinity distribution for Mobile River and Bay and are presented in Table VI. These values are used in the determination of fresh or river water volumes in Mobile River and Bay and give a measure of the observed fresh water accumulation in the bay.

T-S diagrams were constructed for all stations at the ebb and flood tide (i.e. Figure VIII). The effects of the observed temperature inversions are interesting. The wide latitude in temperatures between ebb and flood tide comparisons is not an effect of tidal variation but rather the result of a "norther" which blew in on the 28th and 29th of October. It is unfortunate that the "norther" separated all ebb tide observations of temperature from the observed flood tide temperature measurements. The explanation for this is that inasmuch as the tidal period for the region is diurnal, a twelve hour period of observation would cover a half tide period. Therefore, with only two people available for the field measurements observations were restricted to the daylight hours.

The tidal variation of salinity for most stations is distinctive, however. It was observed that the greatest salinity deviation occurred near the mid-bay and mouth of the estuary and at all depths.

C. Circulation.

The circulation of any water body is probably the most important feature in the explanation of mixing and flushing for that water mass. At the same time it is certainly the most difficult feature to explain satisfactorily for any water body, partially enclosed in an irregular basin and complicated by many different natural effects. River flow, tides, wind, bottom topography, density differences, evaporation, depth, bottom roughness, internal waves and surges are but a few of the variables entering into the explanation of the circulation in an estuary. Since the observed circulation is the sum total of the effects imposed by many factors, any explanation of the mechanics of the circulation requires an understanding of the proportionate degree to which each constituent factor contributes to the total effective pattern of circulation. Some factors which have been listed are ignored or can be assumed to contribute negligible disturbances to a pattern of fluid flow (i.e. if the basin be deep enough, ignore bottom stresses). Evaporation losses are often ignored if precipitation is the dominant of the two. The effects of wind stress are often disregarded also for a region of steady gentle to moderate winds. The usually irregular shoreline and/or bottom topography is most difficult to consider, therefore, these factors are disregarded or modified to simplicity (i.e. flat bottom, straight coast, et cetera).

For a rigorous interpretation of the circulation of Mobile Bay, it is necessary to consider all effects, although five are probably dominant. An attempt to explain the circulation of such a system on a rigorous mathematical basis is impossible at this time, although a few oceanographers have attempted to define simple cases of flow, considering the effects of only one or two parameters at a time on a rigorous basis, i.e. Pritchard (16), Stommel (22), Cameron (2). Little has been accomplished from a three dimensional analysis without losing the necessary rigor. The best compromise appears to be the statistical analysis, accepting a mean evaluation of the circulation from observation and records over a considerable length of time. One year's seasonal observations would produce a very rough picture of what is taking place in a region and would give at least a fair interpretation of the variation in circulation with the seasons of the year. This time interval should be the minimum acceptable for such an analysis. Five to ten years' observations of an estuary would be more satisfactory from the statistical point of view, but undesirable as regards time and expense.

The obvious alternative is an improved theory for a more suitable explanation of estuaries both physically and mathematically. Pritchard (16) refers to two principal theoretical studies of the dynamics of estuarine circulation by Stommel, 1951, (20) on a deep fjord type estuary, and Cameron, 1951, (2) on a similar type estuary in which bottom friction and Coriolis terms may be neglected. Alberni Inlet, Canada, was the model used for the study and application of both theories.

The two charts presented (Figures XVI and XVII) illustrate at the ebb tide and the flood tide an interpretation of the horizontal surface water movement from observed station velocities. The spacing of the streamlines is not a measure of the velocity magnitudes, but is a result of the author's intuition only. The vectors attached to each station indicate the measured magnitude and direction of velocity at that station.

During the early flood tide, water moves into the bay through the entire section of main pass and appears to be deflected to the right (east) of the entrance but gradually swings back toward the left and sets in a northerly to north-easterly direction.

Water which flows from Bon Secour River and Bay and from the intercoastal canal toward the west complicate the main flow from the Gulf - local eddies are in evidence and mixing must be good at the boundary between the two "wator masses". It is evident that water in Bon Secour Bay acts as a buffer for the incoming flood tide, slowing its initial jet-like entrainment and associated velocities and deflecting the flow from its easterly swing back toward the north or upper bay.

At the early flood tide from the main pass water is still ebbing through Pass Aux Herons, and it is not until fifteen minutes to an hour later that Pass Aux Herons starts flooding in a north-easterly direction. It is apparent that this secondary inflow further complicates the main flow through the south pass, resulting in turbulences at the water boundaries and good mixing.

The predominant water movement on the flooding tide is at first to the right or east and then north indicating an overall horizontal counter-clockwise circulation. River flow from the north is deflected to the west and flows rather continuously down the western side of the bay. At flood stage this river water movement is slowed, piled up and possibly is pushed back near the bottom, but at the surface it is observed that this water will on the whole continue to move downstream toward the Gulf.

At the ebb tide, water of the entire bay will progress toward the outlets, rather uniformly and in one dominant direction - south. The flow appears far less complicated than for flood tide flows and observed velocities are more uniform throughout, both in direction and magnitude.

No measure of vertical flows can be made. A vertical circulation, however, is inferred from the evidence of convergence lines or foam lines, sometimes referred to as tide lines (5,23) and from the presence of slicks on the water surface. All of these phenomena were observed during the October survey. It is further inferred as a consequence of the evidences given for convergence that there must be regions of divergence. These, however, are not so easily observed or defined. Figure IX illustrates the observed vertical pattern of flow and velocity for a model estuary based on a two layer system. A similar illustration of the distribution of horizontal flow in a vertical section is presented by Nakano, 1947, (11) for different shaped estuaries containing homogeneous fluids. These are flows induced by steady winds over an enclosed basin.

Briefly, there is evidence to support a counter-clockwise horizontal circulation for Mobile Bay, which has super-imposed on it regions of convergence and divergence indicating a complicated vertical circulation locally, but over the whole bay a more simple vertical pattern of flow related to the wind flow over the bay and/or a flow distribution observed in two-layer systems (Figure IX).

Toward the head or inner part of the estuary little change is observed in the salinity as a result of tidal variation, except possibly at the surface. In this region the river flow appears to be the controlling factor in the observed salinity variations. In all cases where a variation of salinity between ebb and flood stages is observed, the greatest variation occurred near the water surface. Figure IX a and b, after Farmer (6), illustrates the salt wedge profile and flow pattern derived from a model study of a simple estuary at Woods Hole Oceanographic Institute, and agrees in general with the observed vertical distributions of salinity and velocity along the ship channel in Mobile Bay.

D. Mass Transport

An attempt was made to evaluate the mass transport relations across different sections of the bay, but insufficient current observations in time resulted in conservative values for the mean velocities and the consequent transport volumes. For this study several assumptiors were made which, from the results, are evidently invalid. The first assumption made was that the change in water level height in time varied as the function of a sine wave. This is approximately true, therefore, it was further assumed that knowing the phase point of any observation the observed value (i.e. velocity) which varies directly as the tide, could be normalised to a maximum value for the 1/2 tide period. In the instance of velocity the maximum normally occurs at the mid-tide or, as a function of cos θ, when $\theta = 0, \pi, 2\pi$, et cetera. Knowing the maximum current velocity of a flood or an ebb tide which varies as a function of the cosine wave, the mean velocity (u) should therefore be the mean of the cosine distribution of velocity. This was determined from the following relation:

$$\bar{u} = \frac{2}{\pi} \int_0^{\frac{\pi}{2}} u d\theta$$

where $u = \cos\theta$

and $\bar{u} = \frac{2}{\pi}$

Next it was necessary to approximate a mean velocity with depth from only two observations of current in time and space at a station. A surface and bottom current measurement at each station for the different tide stages was made for the survey. A weighted mean of the two current observations was made assuming a straight line distribution from surface to bottom. This is approximately true over a flat bottom for channel flow, although the variation of velocity probably more nearly approximates a logarithmic function of the distance (y) from the interface ($y = \delta$) of a laminar layer. In the laminar layer which is adjacent to the bottom ($y = 0$) the velocity will vary approximately linearly as the vertical distance (δ) from the bottom. (19)

Thus for each significant change of the depth of the water where velocity observations were taken, a mean velocity is computed for the cross sectional area in the vicinity over one tide (i.e. ebb or flood). This mean velocity is used to determine the mass transport volumes of water which pass through the cross-section during an ebb or a flood tide. The difference in the two volumes should equal the river flow volume for one complete tidal cycle less evaporation, if the cross-section transverses the entire width of the estuary.

The method described above gave conservative values of mass transport at the major outlet passes of the estuary as compared to the volume of water which should have been moved on the basis of a carefully determined tidal prism or intertidal volume. The mean intertidal volume computed for Mobile Bay is $516 \times 10^6 M^3$ of water. The total mass transport volume removed on the ebb tide was $460 \times 10^6 M^3$, or approximately 11% too little water. The transport volume entrained on the flood tide was $430 \times 10^6 M^3$. The difference between ebb and flood tide transport volumes of $30 \times 10^6 M^3$ is of the order of magnitude of the river flow ($23.2 \times 10^6 M^3$) for the same time interval, but does not account for a possible decrease due to evaporation (estimated $5 \times 10^6 M^3$/day, Jacobs, 1951) (7). Twenty-eight per cent of the total transport volume expelled from the bay at the ebb tide passes through the smaller southwest pass, or Pass Aux Herons, while the remainder of the transport volume is removed through the main pass. Mean excursion lengths per tide through these passes amount to approximately 7.5 miles per flood tide and 8 miles per ebb tide, producing a non-tidal drift of 0.5 miles per day (tidal cycle) as the resultant of ebb and flood tidal excursions. If the non-tidal drift figure of 1/2 mile (nautical) per day is a reliable measure of the non-tidal drift rate for the entire bay, an approximate flushing time of fifty-four days is implied by this figure (length of the estuary is twenty-seven nautical miles). This assumes that the water is thoroughly mixed during each 1/2 nautical mile of drift and does not return on successive flood tides to a previous point or position occupied in the bay.

E. Tidal Flushing of Mobile Bay.

Tidal flushing for the bay was determined by Ketchum's modified tidal prism theory, described in section III, and the results of the theory were checked against observed distributions of fresh water accumulation (viz. salinity). Calculated values of fresh water accumulation (Table VIII) were very conservative in comparison to observed values of fresh water accumulation (Table VI). The deviation which becomes excessive at the Gulf end of the estuary is due in part to incomplete horizontal mixing and the use of an exaggerated salinity (34‰) as the mean Gulf salinity available for flushing.

Escaping volumes or those volumes of mixed water which are available for dilution of pollution are implied in the tabulated local tidal prism. (Tables IV and V) The escaping volumes V_e are defined by Ketchum as:

$$V_e = \frac{R}{f}$$

where (R) is river flow per tidal cycle and (f) is the ratio of river water present in the mixture to the total mixture of water in the volume segment.

In the application of Ketchum's tidal prism theory to Mobile Bay, it was necessary first to acquire a hydrographic chart of the area, of a scale and accuracy suitable for measuring reliable areas and volumes. H.O. Chart No. 1266, scale 1:80,000 was found to be satisfactory for the job. The chart was divided into ninety thin vertical sections, bounded laterally by the mean low water shore lines of the bay and river and bounded north and south by one minute intervals of latitude or one nautical mile intervals (Figure X). The chart was contoured at two foot intervals and the enclosed areas integrated with a planimeter. Multiplication of a planimetered area by the mean low water depth of that bottom contour resulted in a volume for that section. All such volumes were summed over the entire basin and tabulated (Table IV). The cumulative summation of the ninety volume segments gave the total mean low water volume for the Mobile rivers and Bay (Table V).

For a reasonable determination of the tidal prism volume of water contained in the related rivers and bay, a mean of the observed tidal height variations was computed from two tide gage records (Figure I) located: 1) at the upper bay in Mobile River, and 2) at Cedar Point near the southwest pass. The mean of these records was 1.7 feet. The mean tide height interval presented by the U. S. Hydrographic Office for the Mobile Bay is 1.5 feet. It followed that a conservative measure of tidal height interval to use would be the mean of 1.5 and 1.7 feet; therefore, 1.6 feet was the accepted mean value used. It should be noted that the variation in tide heights will differ at different points in a locality (i.e. the mean height variation at the main pass is 0.3 feet less than at Mobile, Alabama). Also the mean height variation forty-four miles upstream from Mobile is approximately 0.4 feet less than at Mobile (28).

From the mean height variations determined, it was possible to compute the tidal prism volumes locally and completely for the entire bay. The sum of these volumes with the computed low tide volumes made it possible to determine directly the individual and cumulative high tide volumes for rivers and bay (Table IV and V).

These volume relations are more clearly illustrated by Figure II, from which it is possible to determine directly the volume segments necessary in the tidal flushing theory of Ketchum.

The inner end of the estuary was chosen at nautical mile fourteen (Figure X) on the basis of salinity distribution in the Mobile rivers. It was not possible to survey the river during the October investigation. Salinity data was obtained from the U. S. Corps of Engineers (28) at Mobile, Alabama, which for river flows of 10,000 cfs or less during a two year survey placed the boundary of the salt wedge at mile twenty-three of Mobile River. This corresponds to nautical mile fourteen due north of Mobile. Upon establishing the boundaries and volumes of Segment "O" (Table VII), it was then a simple matter to segment the rest of the bay to the Gulf from Figure II. Exchange ratios are presented in Table VIII and from the same table values of accumulated fresh water are shown using the relation $Q_n = \frac{R}{r}$.

The theory produced a flushing time for this estuary of forty-five days as compared to fifty-four days from the observed data and non-tidal drift estimates. It is not unreasonable to use a mean of the two methods and to say that fifty days is a reliable measure or value of the flushing time for Mobile Bay. Inasmuch as river flow fluctuates almost daily, a range of flushing time is probably a better way of expressing the factor (i.e. forty-five to fifty-four days).

VI. SUMMARY AND CONCLUSIONS

The distribution of the physical factors encountered during a hydrographic survey are presented in the Tables and Figures and display few anomalies as to space and time. Inversions of temperature are graphically illustrated in the T-S Diagrams (Figure VIII) as well as the observed variations in salinity. The sharp drop in the temperature evidenced between ebb tide and flood tide data was the result of a "norther" and not related to tidal variation. Water level changes for two positions in Mobile Bay (Figure I) illustrate the effects on water level of a strong northeast wind for this day.

Circulation patterns are presented in the Figures XVI and XVII for ebb and flood tide. In general a counter-clockwise horizontal circulation and a vertical pattern of horizontal flow such as is illustrated in Figure IX are observed. The circulation is complicated in the lower bay due to the configuration of the shore lines in this region and the location of the two passes. Many foam lines and/or tide lines were observed during the survey, which indicate regions of convergence or sinking (5, 23). No distinctive pattern was evident as the lines meandered in any and all directions and were to be found in most any region of the bay at any time.

On the flooding tide a line of demarcation identified by two distinct colors was noticed in the region of the main pass. This line which was not a foam line appeared to be the boundary between inflowing Gulf water and outflowing turbid river and bay water. It was further observed that this boundary meandered slightly but set generally toward the northeast from the pass mouth, losing its identity after a few miles (three to five) distance from the pass.

A paucity of continuous current veolcity data for all stations in Mobile Bay and the assumptions which were required resulted in poor computations of mass transport. Assumptions which were made in the calculations for transport are discussed in the text. Of several attempts to compute the mass transport relations for different cross-sections in the bay, the most satisfactory computation of mass-volume transports deviated 11 % from the observed intertidal volumes. With these discrepancies in mind the mass transport volumes through the main pass and Pass Aux Herons to the southwest gave mean rates of flow of 7.5 miles per flood tide and 8.0 miles per ebb tide. The flood tide transport volume was $430 \times 10^6 M^3$, and the ebb tide transport volume amounted to $460 \times 10^6 M^3$. The difference of $30 \times 10^6 M^3$ agrees in the same order of magnitude with the expected non-tidal drift of $23.2 \times 10^6 M^3$, but does not account for any possible loss due to evaporation (estimated at $5 \times 10^6 M^3$/tidal cycle). It is gratifying, however, that the non-tidal drift rate (27 miles at 0.5 miles per day) agrees in the same order of magnitude with the calculated flushing time (fifty-four days).

Ketchum's modified tidal prism theory gave reasonable results of the same order of magnitude, at least, as the observed accumulation of fresh water concentration for the bay. It is admitted that even though reasonable agreement is observed for the river and about the first five and one half miles of the inner bay (less than 8% deviation, see Figure IV), the theory fails to give a reasonably accurate determination of the flushing processes for the lower bay. In the lower bay deviations amounted to 25% between observed and calculated determinations of fresh water accumulation, which may be considered excessive. Probable causes for the observed and calculated deviations are explained in the text. It is possible that a more conservative choice of the mean Gulf salinity used, if reduced from 34‰ to 30‰ would decrease the deviation in observed and calculated accumulations of fresh water. This change would not decrease the order of magnitude of error, however, to a point where the theory could be considered an excellent tool in the determination of tidal flushing for all estuaries. The method evidently gives very commendable results for those estuaries (Alberni Inlet, Raritan Bay) which Ketchum studied. Table X gives a comparison of the physical characteristics and results of the Mobile Bay survey with other estuaries to which Ketchum's method has been applied.

Inasmuch as Ketchum's method is a definite improvement over the classical tidal prism theory, and also provides a rapid means of estimating flushing rates for any estuary with a minimum amount of data, it is not to be disregarded as a useful tool. Especially should this be considered in the light that to date the method offered by Ketchum has not been improved to any great extent or replaced by other theories.

In summary it requires forty-five to fifty-four days to flush Mobile Bay for a river flow of 10,000 cfs or less. This implies that, were an atomic bomb to explode near the city of Mobile and cause a radioactive contamination of the water in Mobile Bay, all other factors remaining the same (i.e. a river flow of $23.2 \times 10^6 M^3$), it would require approximately one and two-thirds months to remove the greatest possible quantity of contaminated water from the bay. Of course, at the half-life (twenty-five days) or sooner of the contaminated water, sufficient dilution of the radioactive water with sea water would have probably resulted to render the danger of radioactivity to human welfare ineffective.

The charts, which illustrate the distribution of physical properties, offer the major contribution from the Mobile Bay survey. The pattern of circulation that is discussed can only be inferred from the observed current data, which is meager; from the distribution of salinity; from the results of previous studies from other sources such as Stommel (24); and from the intuition of the author.

Mass transport determinations for the bay were unreliable as a result of insufficient current data and the use of several assumptions which are not valid in the strict sense. In order to have reliable determinations for the mass transport across sections of an estuary, it is necessary to make continuous observations with time for all depths and at several points along the section with a good current meter.

The tidal flushing theory of Ketchum is useful in determining exchange ratios (r), the accumulation of river water (Q_n), and to infer a fair measure of the flushing time all within the same order of magnitude as demonstrated by the measured accumulation of river water for Mobile Bay.

It is concluded that Ketchum's method should not be trusted alone, without adequate supporting salinity and current data from the estuary which is under investigation. In addition, it is concluded that much remains to be done toward the development of new or improved methods, with which to explain the mixing processes and water movements of our bays and harbors.

VII. ACKNOWLEDGEMENT

The author wishes to acknowledge the assistance of Walter Lang Jr., Harold Loesch, and Myrtis Shrode in collecting and processing the data, and other project personnel in typing and drafting. Mr. Robert O. Reid offered many valuable suggestions in the writing of the report.

TEMPERATURE DATA
Mobile Bay, Alabama
1952

Station No.	Time & Date (CST)	Tidal Phase	Surface Temp. °F	3 ft.	5 ft.	7 ft.	10 ft.	15 ft.	20 ft.	Bottom
A-5	1245, X 25		64.2	64.3	64.6	64.9	65.0	66.9	67.1	67.1
A-4	1145, X 25		63.6	63.6	63.6	63.6	63.5	63.4	63.0	63.0
A-6	1335, X 25		64.7	64.7	64.6	65.0	66.2	----	----	66.2
A-10	1700, X 25		64.4	64.6	65.0	66.0	66.4	66.8	66.9	66.9
A-9	0750, X 26		63.7	64.0	64.5	65.2	65.1	----	----	----
A-14	0900, X 26		62.9	62.9	63.0	63.1	----	----	----	63.8
A-15	0940, X 26		63.4	63.5	63.7	64.1	65.2	----	----	65.2
A-16	1025, X 26		64.6	64.8	65.1	65.3	65.7	----	----	65.6
A-19	1326, X 26		66.9	64.9	65.0	65.1	65.8	----	----	65.6
A-18	1418, X 26		66.2	66.1	66.1	66.2	66.6	----	----	66.6
A-21	1000, X 27		63.6	63.6	63.8	64.1	----	----	----	64.1
A-22	1026, X 27		64.4	64.5	64.6	64.9	65.3	----	----	65.3
A-17	1110, X 26		64.6	64.1	64.2	65.0	65.3	----	----	65.2
A-20	1240, X 26		64.7	64.1	64.5	65.0	65.0	----	----	65.0
A-23	1100, X 27		64.7	64.5	64.6	65.0	65.0	----	----	65.0
A-28	1234, X 27		66.4	66.1	65.3	64.9	64.8	----	----	----
A-27	1305, X 27		67.2	66.4	66.2	66.2	66.2	----	----	----
A-26	1530, X 27		68.2	67.5	67.2	67.2	67.2	----	----	67.2
A-25	1410, X 27		68.9	68.0	68.1	68.3	68.8	68.8	68.9	68.9
B-18	0625, X 28		63.3	63.5	63.8	64.1	64.1	----	----	64.1
B-19	0745 X 28		63.7	63.9	64.4	65.5	65.9	66.7	66.9	66.3
Buoy 22	0755, X 28		63.8	64.0	64.9	65.6	65.7	----	----	65.8
B-3	0733, X 30		58.6	58.7	58.8	58.9	58.9	59.0	----	59.2
B-4	0740, X 30		58.9	58.9	58.9	58.9	58.9	----	----	58.9
A-2	0810, X 30		59.0	59.2	59.1	59.0	59.0	----	----	59.1
A-1	0823, X 30		63.5	[illegible]	61.5	61.5	62.0	65.0	65.1	65.1
B-5	0842, X 30		59.1	59.1	59.2	59.3	60.8	63.0	64.9	65.6

TABLE I

TEMPERATURE DATA (continued)
Mobile Bay, Alabama
1952

Station No.	Time & Date (CST)	Tidal Phase	Surface Temp. °F	3 ft.	5 ft.	7 ft.	10 ft.	15 ft.	20 ft.	Bottom
B-6	0903. X 30		60.2	60.3	60.7	61.2	63.6	----	----	63.6
B-7	0925. X 30		57.3	57.4	57.5	57.8	58.2	----	----	58.2
A-8	0954. X 30		57.2	57.3	57.6	57.8	58.1	----	----	58.2
A-13	1018. X 30		58.1	58.2	58.2	58.3	----	----	----	58.4
B-12	1053. X 30		58.6	58.7	58.9	59.2	59.8	----	----	59.8
B-11	1117. X 30		59.9	60.0	60.0	60.4	61.2	----	----	61.2
B-10	1133. X 30		60.7	60.8	61.0	61.3	62.0	64.1	65.1	65.3
B-9	1151. X 30		60.3	60.3	60.1	60.0	60.0	----	----	60.0
B-14	1216. X 30		58.9	58.8	58.8	58.9	58.9	----	----	58.9
B-15	1242. X 30		60.2	60.3	60.4	60.5	62.1	66.6	67.0	67.3
B-16	1303. X 30		59.2	59.1	59.0	58.5	58.6	----	----	58.5
B-17	1329. X 30		59.7	59.7	59.6	59.5	59.3	----	----	59.3
B-20	1356. X 30		58.8	58.8	58.9	59.0	59.0	----	----	59.0
C-19	1416. X 30		59.7	59.8	60.0	60.5	62.6	----	----	62.9
C-18	1434. X 30		60.0	59.6	59.0	58.8	58.8	----	----	58.7
B-24	0815. X 31		57.9	57.9	58.0	58.1	----	----	----	58.0
B-25	0850. X 31		59.4	59.8	61.0	62.0	62.9	63.8	64.2	64.5
B-26	0914. X 31		57.7	57.8	58.1	58.3	58.4	----	----	58.4
B-27	0938. X 31		60.6	59.7	58.3	58.1	59.9	----	----	59.9
B-28	0950. X 31		62.2	63.4	63.3	----	----	----	----	63.3
B-23	1020. X 31		59.4	59.3	59.2	59.1	58.9	----	----	58.9
B-22	1043. X 31		58.6	58.9	59.1	59.9	62.8	64.1	65.2	65.5
B-21	1058. X 31		58.7	58.7	58.7	58.8	58.9	----	----	58.9
Beacon No. 27	1126. X 31		59.2	59.2	59.6	62.6	63.8	65.9	66.0	66.2
D-19	1141. X 31		58.8	58.9	59.1	60.0	62.9	64.8	65.3	65.8
Buoy 19	1204. X 31		59.3	59.1	59.2	59.6	60.9	62.1	63.9	64.9
C-15	1244. X 31		60.8	60.3	60.1	59.9	60.6	62.3	63.3	63.2
C-10	1310. X 31		61.4	61.6	61.9	62.0	63.0	63.7	64.1	64.2

TABLE I. (continued)

TEMPERATURE DATA (continued)
Mobile Bay, Alabama
1952

Station No.	Time & Date (CST)	Tidal Phase	Surface Temp. °F	3 ft.	5 ft.	7 ft.	10 ft.	15 ft.	20 ft.	Bottom
C-5	1333, X 31		64.1	64.1	64.1	64.1	64.2	64.2	64.3	64.6
B-1	1358, X 31		65.4	65.4	65.5	65.6	65.9	66.3	67.1	67.1
B-2	1416, X 31		64.8	64.8	64.8	64.8	64.8	----	----	----
C-3	1451, X 31		62.4	62.4	62.3	62.3	62.1	61.9	61.6	61.6
A-3	1045, X 25		63.3	----	----	----	----	----	----	----
A-7	1435, X 25		64.4	----	----	----	----	----	----	----
A-12	1540, X 25		64.6	----	----	----	----	----	----	----
A-11	1610, X 25		64.9	----	----	----	----	----	----	----
A-10	1655, X 25		64.4	----	----	----	----	----	----	----
Cedar Pt.	1925, X 25		65.7	----	----	----	----	----	----	----
Cedar Pt.	2055, X 25		65.1	----	----	----	----	----	----	----
Cedar Pt.	2240, X 25		65.1	----	----	----	----	----	----	----
Cedar Pt.	0530, X 26		63.0	----	----	----	----	----	----	----
Cedar Pt.	0700, X 26		62.5	----	----	----	----	----	----	----
Mullet Point	1150, X 26		65.0	----	----	----	----	----	----	----
3/4 mi.W Klondike Reef	1205, X 26		64.2	----	----	----	----	----	----	----
C-4	1437, X 31		63.0	----	----	----	----	----	----	----
Fowl R. Reef	1447, X 30		60.7	----	----	----	----	----	----	----
A-24	1442, X 27		66.7	----	----	----	----	----	----	----
Buoy 22	0755, X 28		63.8	----	----	----	----	----	----	----
3/4 mi. . Lab.	0940, X 28		65.2	----	----	----	----	----	----	----

TABLE I. (continued)

SALINITY DATA (0/00)
Mobile Bay, Alabama
1952

Sta. No.	Time(CST) & Date	Tidal Phase	Bottom Depth (ft)	Surface	Upper Quarter	Mid-Depth	Lower Quarter	Bottom
A-3	1039, X 25		19	21.15	----	--	--	21.27
A-4	1133, X 25		20	21.05	----	--	--	21.46
A-5	1245, X 25		33	22.25	----	30.66	--	32.59
A-6	1335, X 25		11	25.06	----	26.46	--	31.15
A-7	1435, X 25		7.5	24.25	24.24	--	25.39	27.30
7.5	1505, X 25			24.24	----	--	--	--
A-12	1540, X 25		10	25.00	----	24.95	--	27.53
A-11	1610, X 25		12	23.15	----	23.25	--	26.82
A-10	1655, X 25		31	20.19	----	30.42	--	31.81
Cedar Pt.	1925, X 25		5	20.29	----	--	--	20.31
Cedar Pt.	2055, X 25		5	21.18	----	--	--	21.09
Cedar Pt.	2240, X 25		5	23.13	----	--	--	23.14
Cedar Pt.	0530, X 26		5	19.60	----	--	--	21.74
Cedar Pt.	0700, X 26		5	18.55	----	--	--	18.68
A-9	0750, X 26		11	20.38	----	25.84	--	29.14
A-14	0900, X 26		11	17.58	----	17.97	--	19.31
A-15	0940, X 26		13	19.87	----	22.09	---	27.00
A-16	1023, X 26		11	20.37	----	23.12	--	27.02
A-17	1110, X 26		11	24.07	----	--	--	26.59
Mullet Pt.	1150, X 26		7	24.04	----	--	--	24.14
3/4 mi. W Klondike Reef	1205, X 26		11	24.09	----	--	--	24.16
A-20	1233, X 26		11	22.90	----	23.04	--	24.29
A-19	1326, X 26		13	1[illegible].53	----	16.76	--	23.38
A-18	1410, X 26		10	1[illegible].30	----	16.08	--	17.79

TABLE II

SALINITY DATA (0/00) (continued)
Mobile Bay, Alabama
1952

Sta. No.	Time (CST) & Date	Tidal Phase	Bottom Depth (Ft)	Surface	Upper Quarter	Mid-Depth	Lower Quarter	Bottom
A-21	0955, X 27		9	14.41	--	14.85	--	15.06
A-22	0923, X 27		12	16.03	--	16.06	--	23.55
A-23	1100, X 27		12	17.84	--	17.86	--	22.79
A-28	1230, X 27		10	17.66	--	18.65	--	20.00
A-27	1305, X 27		10	16.83	--	19.29	--	19.32
A-26	1335, X 27		11	15.08	--	15.57	--	19.14
A-25	1408, X 27		29	12.36	25.23		29.07	29.88
A-24	1442, X 27		8	13.02	--	13.05	--	13.99
Fowl River	1625, X 27							
B-18	0625, X 28		12	16.93	--	16.92	--	21.18
B-19	0740, X 28		23	19.18	--	27.30	--	29.90
Channel Mk. No. 22	0755, X 28		13	19.09	--	25.87	--	25.71
3/4 mi. E Lab.	0940, X 28			22.35	--	--	--	--
B-3	0713, X 30		20	25.32	--	25.82	--	25.93
B-4	0740, X 30		13	25.65	--	25.75	--	25.68
A-2	0810, X 30		13	28.44	--	28.32	--	28.33
A-1	0823, X 30		35	28.67	--	28.90	--	32.77
B-5	0842, X 30		35	26.82	--	31.68	--	33.42
B-6	0903, X 30		10	27.44	--	27.45	--	30.42
B-7	0925, X 30		11	23.88	--	23.84	--	23.92
A-8	0954, X 30		11	23.24	--	23.22	--	23.37
A-13	1018, X 30		9	23.68	--	--	--	24.39
B-12	1053, X 30		10	22.98	--	23.06	--	31.96
B-11	1117, X 30		10	24.08	--	24.20	--	24.69
B-10	1133, X 30		31	24.69	26.26	--	32.03	32.65

TABLE II (continued)

SALINITY DATE (0/00) (continued)
Mobile Bay, Alabama
1952

Sta. No.	Time(CST) & Date	Tidal Phase	Bottom Depth(FT)	Surface	Upper Quarter	Mid-Depth	Lower Quarter	Bottom
B-9	1151, X 30	[illegible]	12	25.79	--	25.96	--	25.92
B-14	1216, X 30	[illegible]	11	20.82	--	22.26	--	22.36
B-15	1242, X 30	[illegible]	35	22.30	24.22	--	32.39	32.77
B-16	1303, X 30	[illegible]	13	21.50	--	21.66	--	20.73
B-17	1329, X 30	[illegible]	10	23.68	--	23.69	--	23.78
B-20	1356, X 30	[illegible]	12	20.77	--	24.00	--	23.91
C-19	1416, X 30	[illegible]	13	17.56	--	20.02	--	24.48
C-18	1435, X 30	[illegible]	13	19.06	--	19.82	--	19.98
Fowl River Reef	1447, X 30	[illegible]	--	18.20	--	--	--	--
B-24	0814, X 31	[illegible]	8	13.86	--	--	--	13.84
B-25	0849, X 31	[illegible]	30	12.68	25.31	--	29.18	31.56
B-26	0914, X 31	[illegible]	11	14.37	--	15.69	--	16.76
B-27	0936, X 31	[illegible]	11	12.03	--	15.07	--	17.93
B-28	0950, X 31	[illegible]	6	11.29	--	--	--	15.15
B-23	1017, X 31	[illegible]	12	19.02	--	19.04	--	19.04
B-22	1043, X 31	[illegible]	32	17.20	24.21	--	31.74	31.97
B-21	1058, X 31	[illegible]	10	15.34	--	15.33	--	15.49
Buoy 27	1124, X 31	[illegible]	33	18.22	19.82	--	30.94	31.90
D-19	1141, X 31	[illegible]	35	18.16	26.10	--	31.64	31.87
Buoy 19	1204, X 31	[illegible]	35	19.95	26.20	--	30.66	31.51
C-15	1244, X 31	[illegible]	25	23.29	24.34	--	29.62	30.52
C-10	1310, X 31	[illegible]	35	25.13	28.23	--	30.52	31.67
C-5	1333, X 31	[illegible]	35	30.95	32.20	--	32.26	32.52
B-1	1358, X 31	[illegible]	35	32.56	32.62	--	33.56	34.07
B-2	1416, X 31	[illegible]	10	32.62	--	32.12	--	32.07
C-4	1437, X 31	[illegible]	12	27.59	--	--	--	27.72
C-3	1451, X 31	[illegible]	23	26.80	--	26.02	--	26.84

TABLE II (continued)

TEMPERATURE-SALINITY DATA
Mobile River, Alabama
October 24, 1945
(After U. S. Corps of Engineers)

Range No.	Sample Depth(ft) Rt.	Mid.	Lft.	Temperature (F°) Surface Only	Salinity (‰) Rt.	Mid.	Lft.
3-Mile	-	0	-	—	—	4.64	—
Creek	-	6	-		—	5.45	—
	-	11	-		—	10.68	—
Chicka-	-	0	-	—	—	1.76	—
saw Bogue	-	20	-		—	17.71	—
R.	-	38	-		—	18.45	—
1	0	0	0	71°	5.02	5.34	5.28
	8	9	9		7.38	7.48	7.91
	14	16	17		10.68	13.34	16.64
2	0	0	0	—	3.23	3.10	3.23
	8	9	9		3.42	5.85	5.02
	14	16	17		4.72	12.38	17.71
3	0	0	0	71°	1.28	0.93	1.05
	6	8	8		1.37	1.41	1.31
	11	14	14		3.52	4.39	4.38
3A	0	0	0	71°	0.83	0.89	0.80
	6	7	9		1.09	1.05	0.93
	10	13	17		1.34	1.73	2.72
3B	0	0	0	71°	0.70	0.73	0.80
	10	10	5		0.70	0.73	0.80
	19	19	9		1.34	1.02	0.80
4	0	0	0	71°	0.12	0.21	0.13
	12	18	16		0.15	0.13	0.14
	24	35	30		0.37	0.51	0.20
5	0	0	0	70°	0.04	0.04	0.04
	16	16	16				
	31	31	30			Fresh Water	
6	0	-	0	69°	0.05	—	0.05
	23	-	8		0.05	—	0.05
	45	-	14		0.05	—	0.05
7	0	-	0	69°	0.04	—	0.04
	5	-	13		0.04	—	0.03
	9	-	24		0.04	—	0.04
8	0	-	0	68°	0.05	—	0.04
	17	-	10		0.04	—	0.05
	31	-	18		0.04	—	0.05

TABLE II, a

CURRENT AND WIND DATA
Mobile Bay, Alabama
1952

Station No.	Time & Date (CST)	Tidal Phase	Current Velocity Surface Direction (° from true N)	Surface Speed (knots)	Bottom Direction (° from true N)	Bottom Speed (knots)	Wind Velocity Direction (° from true N)	Wind Speed (knots)
A-3	1039, X 25		220	2.06	220	2.53	045	12
A-4	1133, X 25		170	0.44	170	0.30	350	9
A-5	1245, X 25		210	0.88	210	0.48	030	8
A-6	1335, X 25		210	0.54	220	0.16	030	9
A-7	1435, X 25		320	0.48	320	0.26	000	8
A-12	1540, X 25		180	0.26	180	0.24	000	7
A-11	1610, X 25		150	0.28	035.	0.59	000	6
A-10	1655, X 25		000	0.24	000	0.59	000	7
Cedar Pt.	1925, X 25		090	0.82	---	---	335	
Cedar Pt.	2055, X 25		090	0.93	---	---	330	
Cedar Pt.	2240, X 25		090	0.98	---	---	340	
Cedar Pt.	0530, X 26		280	0.37	---	---	000	
Cedar Pt.	0700, X 26		270	0.63	270	0.50	010	
A-9	0750, X 26		195	0.88	015	0.22	010	10
A-14	0900, X 26		185	1.02	185	0.74	010	8
A-15	0940, X 26		190	0.86	010	0.22	010	6
A-16	1023, X 26		180	0.59	180	0.22	000	3
A-17	1110, X 26		230	0.28	230	0.11	310	1
Mullet Pt.	1150, X 26		---	---	---	---	330	1
3/4 mi. W Klondike Rf.	1205, X 26		---	---	---	---	330	1
A-20	1233, X 26		180	0.63	---	0.13	290	1
A-19	1326, X 26		200	0.65	170	0.22	270	<1
A-18	1410, X 26		200	0.40	180	0.17	250	<1

TABLE III

CURRENT AND WIND DATA (continued)
Mobile Bay, Alabama
1952

Station No.	Time & Date (CST)	Tidal Phase	Current Velocity Surface Direction (° from true N)	Surface Speed (knots)	Bottom Direction (° from true N)	Bottom Speed (knots)	Wind Velocity Direction (° from true N)	Wind Speed (knots)
A-21	0955, X 27		190	0.52	190	0.24	335	4
A-22	0923, X 27		160	0.26	170	0.16	345	3
A-23	1100, X 27			0.37	180	0.11	340	6
A-28	1230, X 27			0.35			310	4
A-27	1305, X 27		180	0.37	170	0.09	320	2
A-26	1335, X 27		180	0.37	140	0.07	320	4
A-25	1408, X 27		190	0.35	180	0.03	010	2
A-24	1442, X 27		180	0.15		0.03	---	0
Fowl River	1625, X 27		---	----	---	----	---	--
B-18	0625, X 28		045	0.37	310	0.28	270	12
B-19	0740, X 28		005	0.69	000	0.37	320	12
Channel Mk No. 22	0755, X 28		---	----	---	----	---	--
3/4 mi. E Lab.	0940, X 28		---	----	---	----	360	25
B-3	0713, X 30		245	0.72	---	----	270	16
B-4	0740, X 30		325	0.68	---	----	---	--
A-2	0810, X 30		340	0.72	---	----	060	12
A-1	0823, X 30		040	0.91	040	0.78	---	--
B-5	0842, X 30		080	0.72	---	----	060	14
B-6	0903, X 30		000	0.78	---	----	---	--
B-7	0925, X 30		230	0.40	040	0.46	050	10
A-8	0954, X 30		090	0.40	090	0.33	050	10
A-13	1018, X 30		020	0.28	330	0.28	050	8
B-12	1053, X 30		250	0.37	250	0.35	070	6
B-11	1117, X 30		240	0.46	240	0.40	---	--

TABLE III. (continued)

CURRENT AND WIND DATA (continued)
Mobile Bay, Alabama
1952

Station No.	Time & Date (CST)	Tidal Phase	Current Velocity Surface Direction (° from true N)	Surface Speed (knots)	Bottom Direction (° from true N)	Bottom Speed (knots	Wind Velocity Direction (° from true N)	Wind Speed (knots)
B-10	1133, X 30		340	0.28	000	0.42	075	9
B-9	1151, X 30		350	0.46	050	0.40	—	-
B-14	1216, X 30		315	0.30	340	0.50	020	6
B-15	1242, X 30		340	0.35	010	0.63	060	2
B-16	1303, X 30		035	0.33	030	0.33	—	-
B-17	1329, X 30		050	0.37	050	0.46	150	10
B-20	1356, X 30		160	0.20	360	0.17	—	0
C-19	1416, X 30		000	0.17	030	0.37	—	0
C-18	1435, X 30		020	0.13	060	0.22	—	0
Fowl River Reef	1447, X 30		—	—	—	—	—	0
B-24	0814, X 31		240	0.35	—	—	030	8
B-25	0849, X 31		160	0.72	160	0.37	020	7
B-26	0914, X 31		220	0.24	240	0.24	—	-
B-27	0936, X 31		270	0.20	090	0.24	040	4
B-28	0950, X 31		240	0.30	—	—	—	-
B-23	1017, X 31		020	0.16	000	0.28	350	10
B-22	1043, X 31		150	0.24	150	0.63	—	-
B-21	1058, X 31		160	0.20	160	0.13	020	4
Buoy 27	1124, X 31		—	—	—	—	—	-
D-19	1141, X 31		140	0.20	140	1.20	000	2
Buoy 19	1204, X 31		—	—	—	—	—	-
C-15	1244, X 31		025	0.33	000	0.68	350	4
C-10	1310, X 31		025	0.65	015	0.84	—	-
C-5	1333, X 31		340	0.37	000	0.61	000	1
B-1	1358, X 31		290	0.63	120	0.54	135	7
B-2	1416, X 31		045	0.61	045	0.59	130	2
C-4	1437, X 31		—	—	—	—	—	-
C-3	1451, X 31		060	1.96	060	1.51	—	0

TABLE III (continued)

MOBILE RIVER-BAY VOLUME SEGMENTS

Distance from Mobile (Nautical Miles N. and S.)	Low Tide ($X 10^6 M^3$)	Tidal Prism ($X 10^6 M^3$)	High Tide ($X 10^6 M^3$)
16	307.20	28.20	389.40
15	14.82	0.90	15.70
14	19.01	1.20	20.21
13	16.30	1.21	17.50
12	10.98	1.25	12.22
11	10.31	1.44	17.93
10	10.13	1.40	16.50
9	16.61	1.22	17.62
8	25.70	1.64	25.31
7	20.20	2.40	22.60
6	25.80	2.60	26.40
5	29.32	3.98	35.51
4	30.10	3.63	33.70
3	23.98	3.03	27.03
2	32.30	3.40	37.70
1	27.92	6.50	34.50
0	23.30	6.80	35.10
1	28.10	9.60	37.70
2	40.60	11.80	32.40
3	50.64	11.98	62.63
4	53.70	12.02	70.73
5	68.00	12.30	80.30
6	77.70	14.00	91.70
7	87.37	14.80	102.80
8	89.51	14.54	104.00
9	89.02	14.40	103.40
10	90.98	14.99	106.00
11	83.62	13.43	97.05
12	81.12	13.94	95.06
13	86.30	14.96	101.40
14	97.26	15.50	112.70
15	98.33	15.40	113.70
16	97.31	16.11	113.40
17	109.70	18.10	127.80
18	128.70	20.80	149.50
19	146.00	22.50	168.50
20	154.30	24.32	178.90
21	104.20	25.54	190.70
22	184.40	28.10	212.30
23	202.20	29.04	231.30
24	192.50	27.13	219.60
25	122.60	21.97	154.60
26	80.81	10.90	91.70
27	14.82	0.91	15.63

TABLE IV

MOBILE RIVER-BAY
CUMULATIVE VOLUME SEGMENTS

Distance from Mobile (Nautical Miles N. and S.)	Low Tide ($X\ 10^6M^3$)	Tidal Prism ($X\ 10^6M^3$)	High Tide ($X\ 10^6M^3$)
16	307.20	22.20	329.40
15	322.00	23.20	345.20
14	341.00	24.40	365.40
13	357.30	25.61	382.90
12	368.30	26.90	395.10
11	384.80	28.30	413.10
10	399.90	29.70	429.60
9	416.50	30.50	447.40
8	440.20	32.32	472.70
7	480.40	34.90	493.30
6	484.10	37.50	521.60
5	513.50	41.80	554.90
4	543.50	45.12	568.60
3	557.50	48.20	615.10
2	599.80	53.60	653.40
1	627.70	60.12	687.80
0	656.00	66.90	722.20
1	694.10	76.50	760.80
2	724.00	83.30	812.90
3	775.30	100.30	875.50
4	834.00	112.30	946.30
5	902.00	124.60	1027.00
6	979.70	138.60	1118.00
7	1068.00	153.40	1221.00
8	1157.00	167.90	1325.00
9	1246.00	182.20	1428.00
10	1337.00	197.20	1534.00
11	1421.00	210.70	1631.00
12	1502.00	224.60	1726.00
13	1588.00	239.60	1823.00
14	1686.00	253.00	1941.00
15	1784.00	270.40	2054.00
16	1881.00	286.50	2169.00
17	1991.00	304.60	2296.00
18	2120.00	325.40	2445.00
19	2266.00	347.90	2614.00
20	2420.00	372.20	2792.00
21	2584.00	398.80	2983.00
22	2769.00	426.90	3195.00
23	2971.00	455.90	3427.00
24	3164.00	483.00	3647.00
25	3296.00	505.00	3801.00
26	3377.00	515.90	3893.00
27	3392.00	516.70	3909.00

TABLE V

MOBILE RIVER-BAY CUMULATIVE
FRESH WATER VOLUME SEGMENTS

Distance from Mobile (Nautical Miles N. and S.)	Low Tide ($X\ 10^6 M^3$)	High Tide ($X\ 10^6 M^3$)	Mean Tide Level ($X\ 10^6 M^3$)
16	307.20	329.40	318.30
15	322.00	345.00	333.50
14	340.90	365.20	353.10
13	357.00	382.50	369.70
12	367.80	394.40	381.10
11	383.80	411.80	397.80
10	397.60	426.80	412.20
9	411.80	442.20	427.00
8	431.00	462.70	446.90
7	446.50	480.00	463.20
6	464.20	499.60	481.90
5	465.60	523.90	504.70
4	506.90	547.80	527.40
3	523.40	566.70	545.00
2	544.80	592.60	568.70
1	562.70	616.00	589.30
0	580.20	639.40	609.70
1	596.80	663.80	630.10
2	619.40	696.30	657.40
3	645.10	733.50	689.20
4	675.40	773.60	723.70
5	709.00	817.20	762.10
6	747.30	865.70	805.40
7	790.40	918.30	853.20
8	832.70	969.10	899.60
9	874.20	1018.00	945.00
10	917.00	1068.00	991.20
11	954.80	1112.00	1032.00
12	990.90	1151.00	1070.00
13	1029.00	1191.00	1109.00
14	1070.00	1234.00	1151.00
15	1110.00	1274.00	1192.00
16	1148.00	1314.00	1231.00
17	1188.00	1356.00	1271.00
18	1230.00	1400.00	1315.00
19	1274.00	1446.00	1360.00
20	1318.00	1491.00	1405.00
21	1362.00	1539.00	1451.00
22	1410.00	1595.00	1503.00
23	1465.00	1653.00	1559.00
24	1515.00	1705.00	1610.00
25	1546.00	1738.00	1642.00
26	1563.00	1752.00	1658.00
27	1566.00	1753.00	1660.00

TABLE VI

SEGMENTATION OF MOBILE RIVER AND BAY USING A RIVER FLOW OF 23.2 X $10^6 M^3$/TIDAL CYCLE (9500 cfs)

Segment No.	Length of Segment (Nautical Miles)	Distance from Mobile (Nautical Miles)	Cumulative Volumes (X $10^6 M^3$) Low Tide Σ_o^n V	Tidal Prism Σ_o^n P	High Tide Σ_o^n(P+V)
0	23	-15	322	23.2	345
I	15	0.6	667	72.0	739
II	6.4	7.0	1061	154.0	1215
III	5.5	12.5	1537	230.0	1767
IV	5.1	17.6	2089	318.0	2407
V	4.2	21.8	2729	418.0	3147
VI	5.7	27.5	3469	520.0	3989

TABLE VII

DETERMINATION OF THE ACCUMULATION OF RIVER WATER IN MOBILE RIVER AND BAY, USING A RIVER FLOW OF 23.2 X $10^6 M^3$/TIDAL CYCLE (9500 cfs)

Segment No.	Length of Segment (Nautical Miles)	Local Volumes ($X 10^6 M^3$) Intertidal (P_n)	High Tide ($P_n + V_n$)	Exchange Ratio r	Accumulation Q_n	$\Sigma_o^n Q$
0	23	23.2	345	0.067	345	345
I	15	48.8	394	0.124	187	532
II	6.4	82.0	476	0.172	135	667
III	5.5	76.0	552	0.138	168	835
IV	5.1	88.0	640	0.137	169	1004
V	4.2	100.0	740	0.135	172	1176
VI	5.7	102.0	842	0.121	192	1368

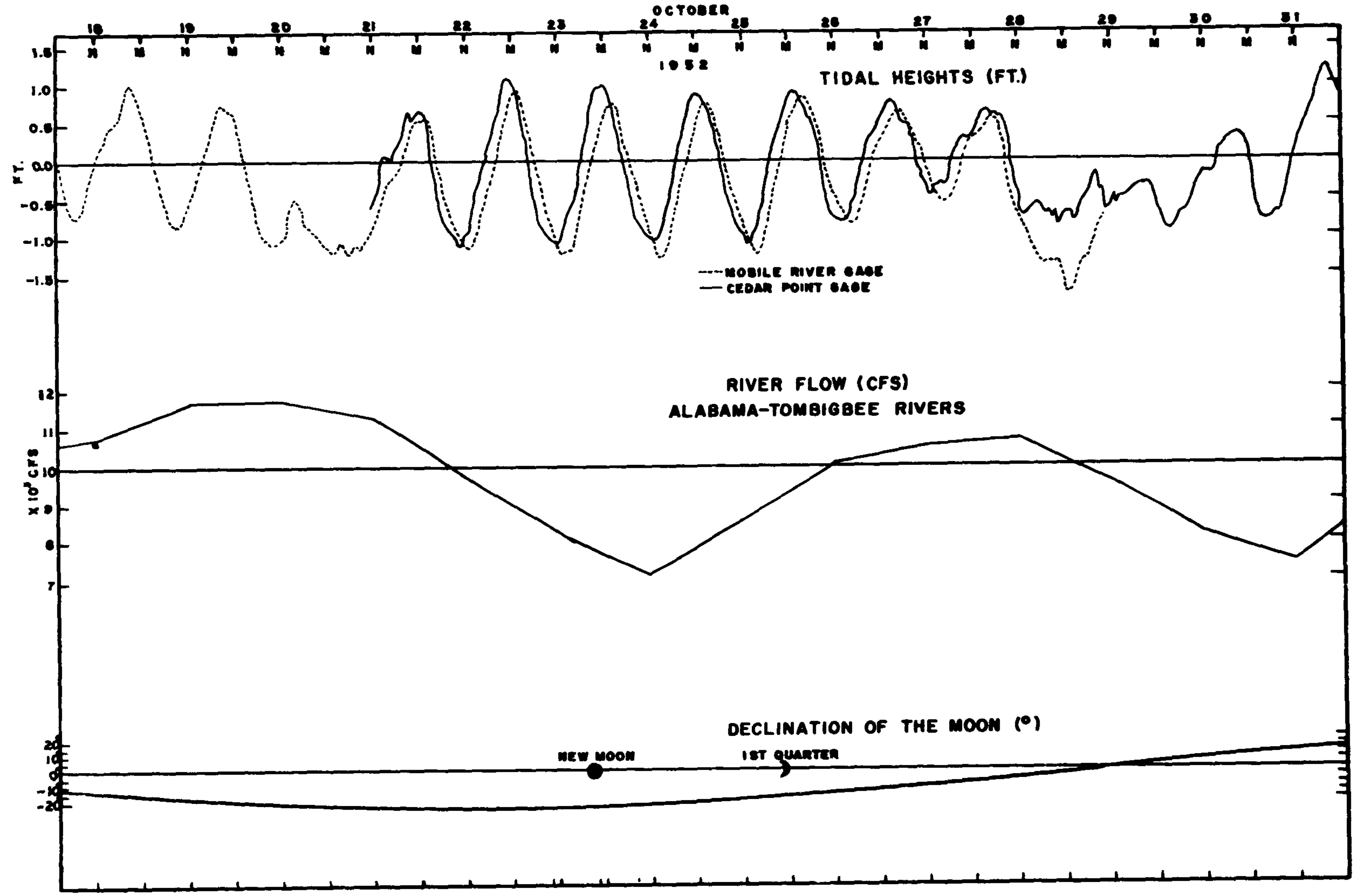
TABLE VIII

COMPARISON OF MOBILE BAY SURVEY
WITH THREE OTHER ESTUARIES

Estuary Characteristics	Mobile River & Bay	Raritan River* & Bay	Alberni* Inlet	Great* Pond
Surveyed Length in Nautical Miles	43	20	20	1.5
Surface Area Sq. Nautical Miles	297 +	40	16	0.375
Maximum High Tide depth, feet	60	40	1000	9.0
Depth of Mixed Layer, feet	10 to total	Total	30	3.5-5
Mean Range of Tides, feet	1.5	5.2	6.4	1.5
Tidal Prism Volume (10^6 x ft^3)	18,220	9200	4000	7.6
River Flow per Tidal Cycle($10^6 ft^3$)	819	33	120	0.5
Ratio $\frac{\text{Prism Volume}}{\text{River Flow}}$	22	279	33	15

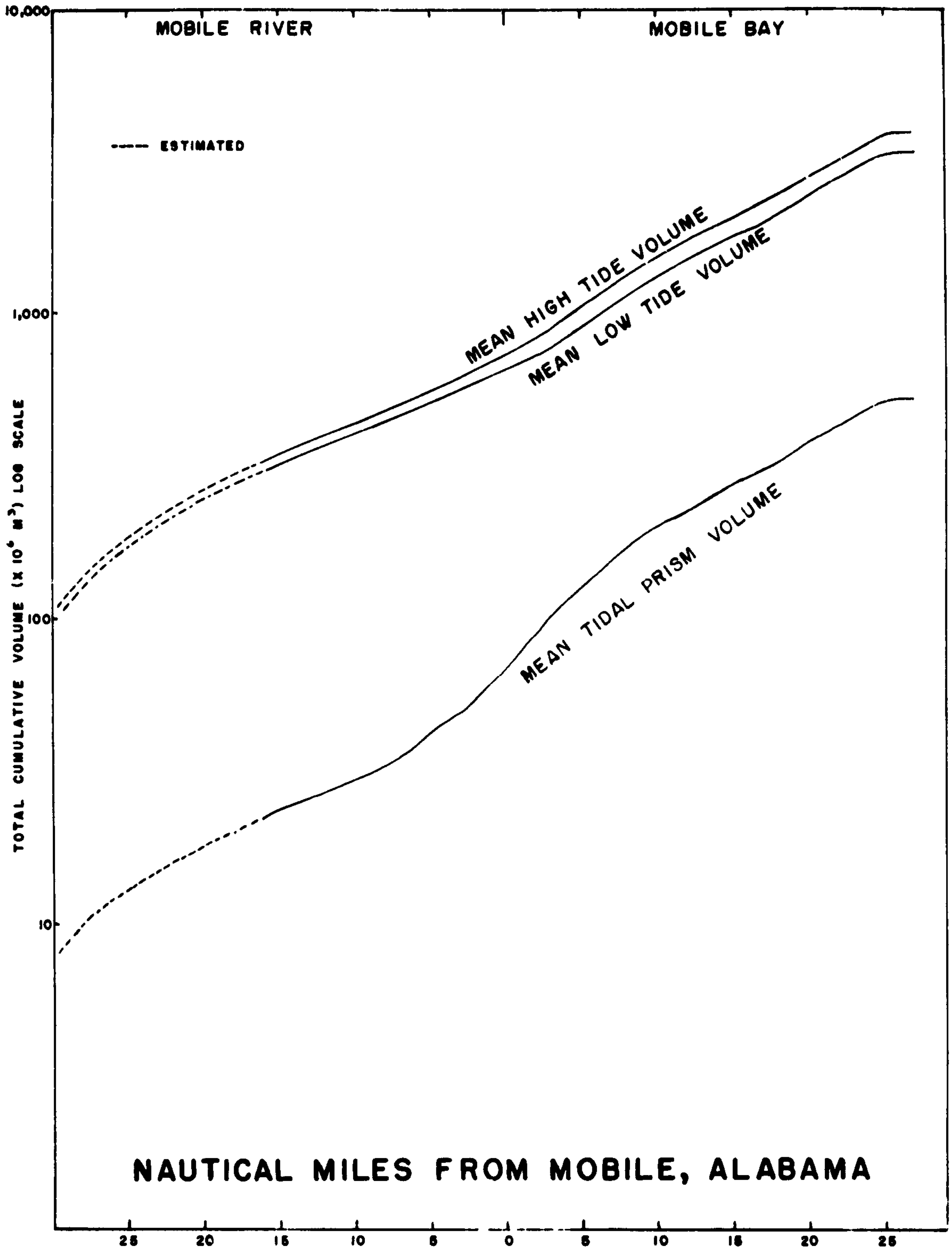
* After Ketchum, 1951

TABLE IX



OCTOBER
1952
TIDAL HEIGHTS (FT.)
MOBILE RIVER GAGE
CEDAR POINT GAGE
RIVER FLOW (CFS)
ALABAMA-TOMBIGBEE RIVERS
DECLINATION OF THE MOON (°)
NEW MOON
1ST QUARTER

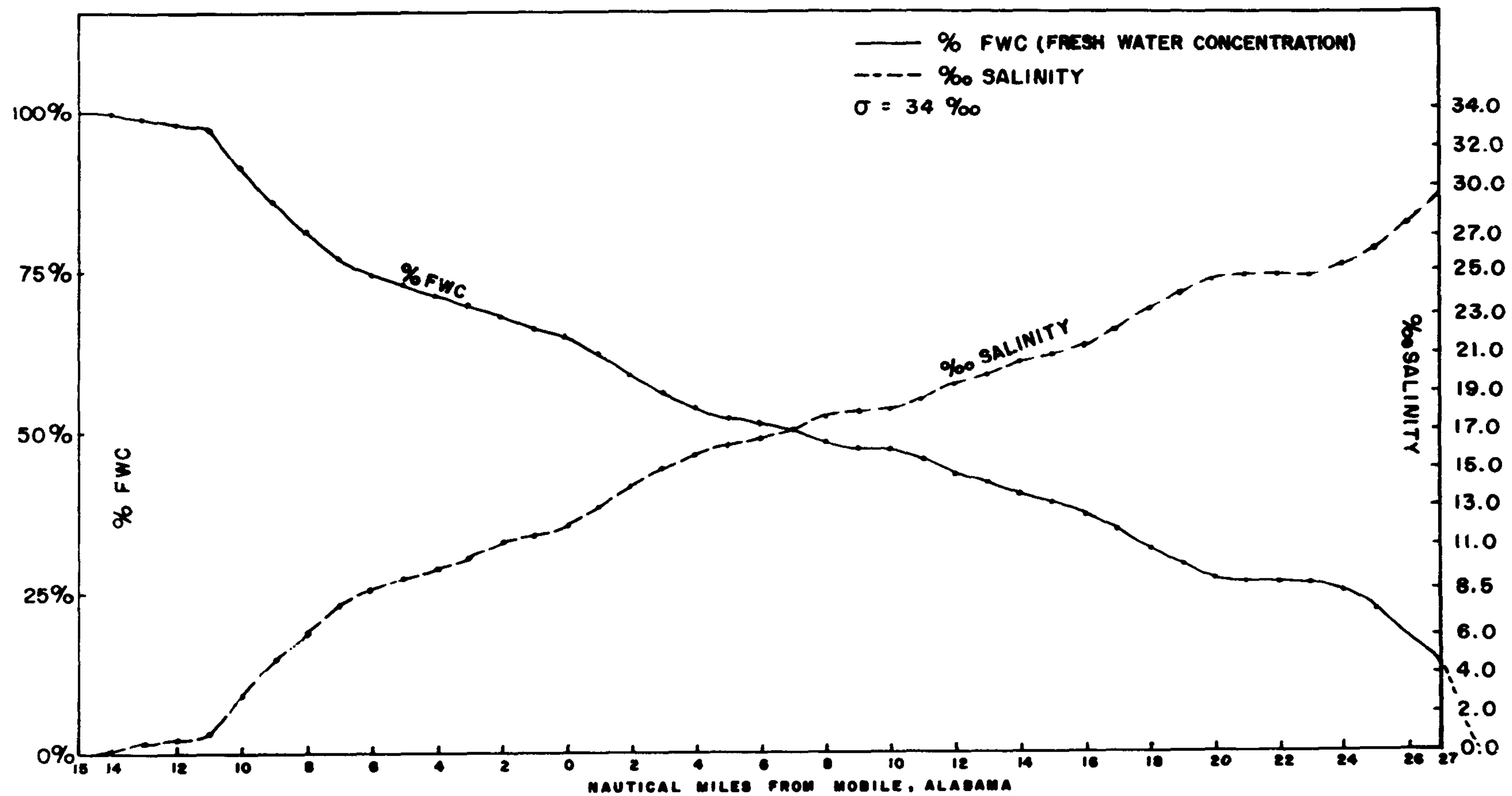
FIGURE 1



CUMULATIVE WATER VOLUMES

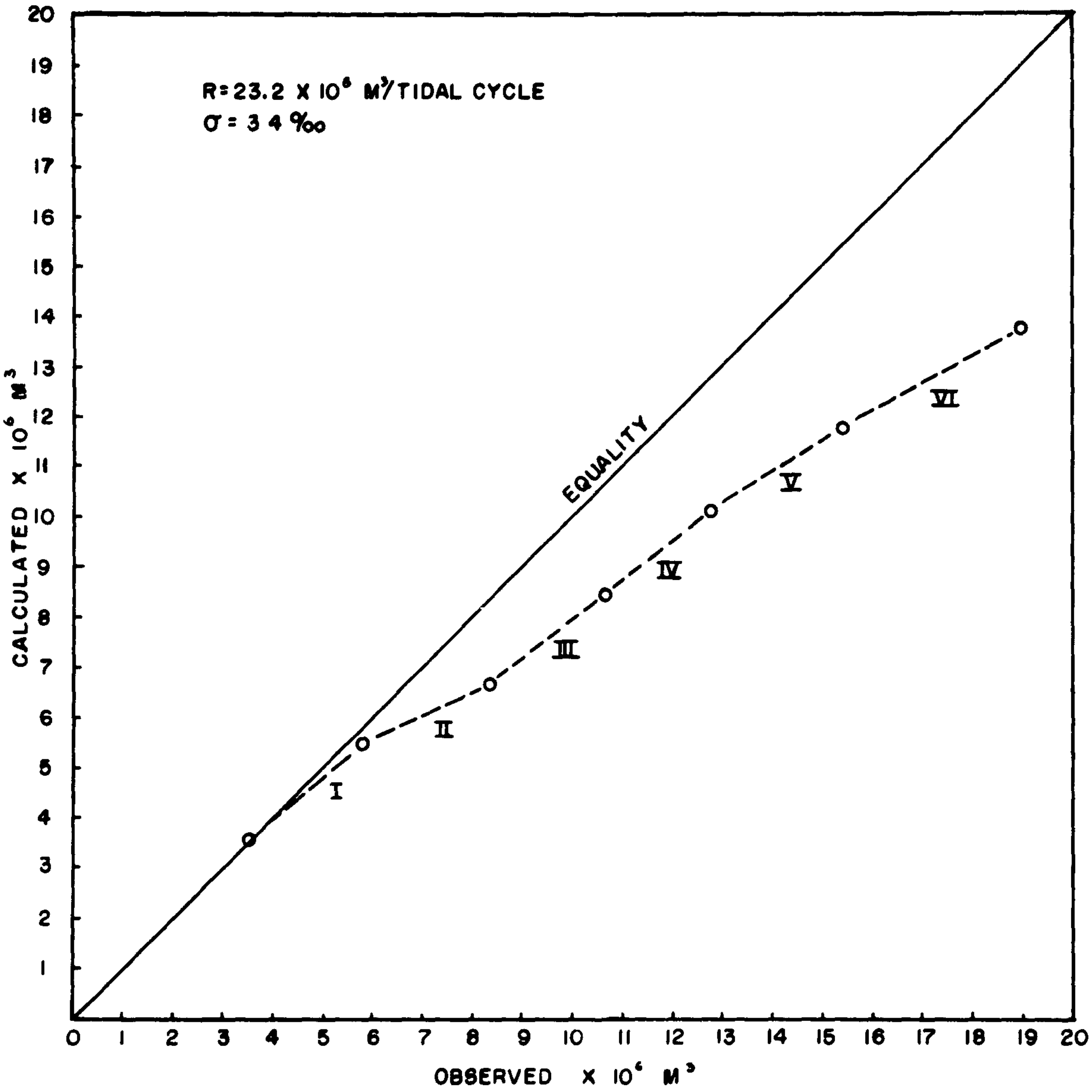
MOBILE RIVER AND BAY, ALABAMA
RIVER FLOW AT $23.2 \times 10^6 M^3$/TIDAL CYCLE

FIGURE II



(%) FWC AND (‰) SALINITY
FOR MOBILE RIVER AND BAY, ALABAMA
OCTOBER, 1952

FIGURE III



COMPARISON OF OBSERVED AND CALCULATED ACCUMULATION OF FRESH WATER IN MOBILE RIVER AND BAY

FIGURE IV

TEMPERATURE–DEPTH SECTION, UPPER MOBILE BAY
(°F)

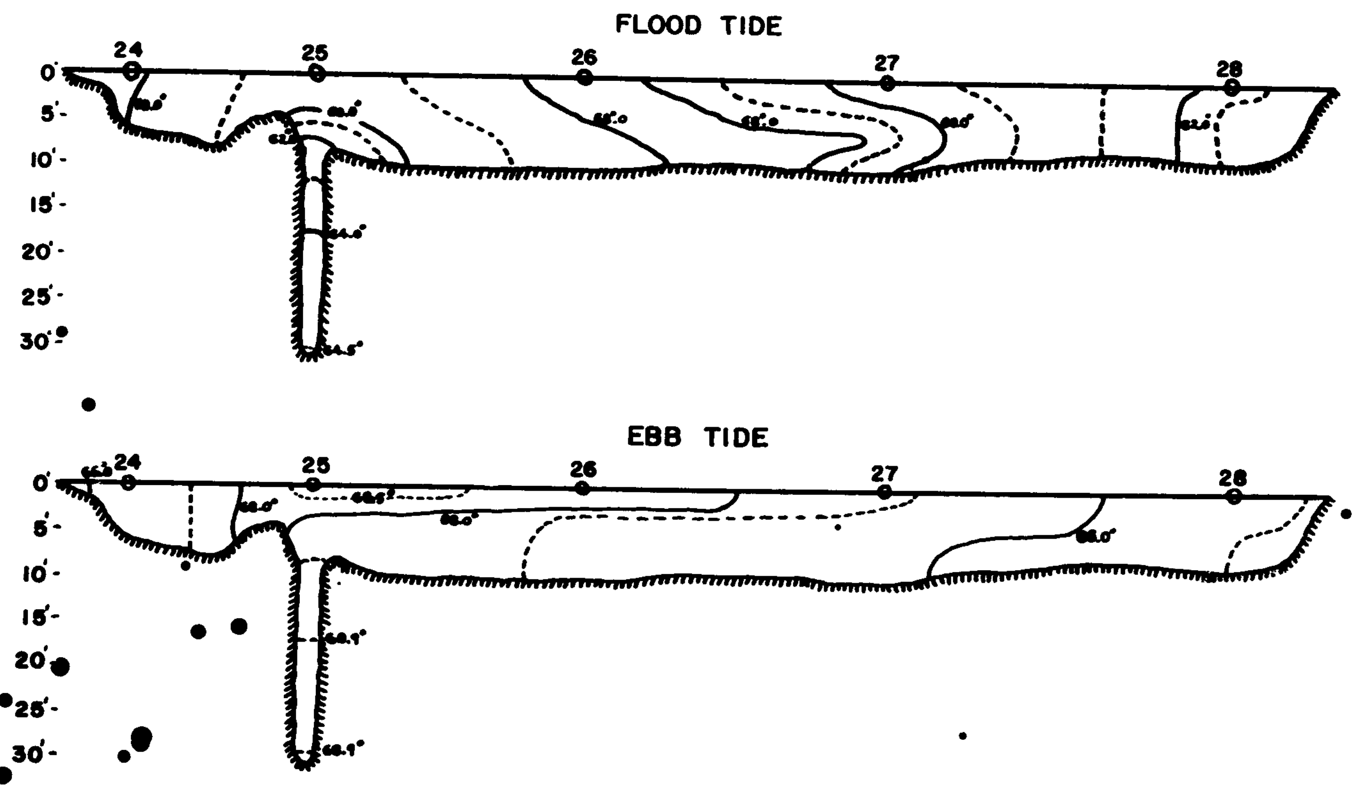
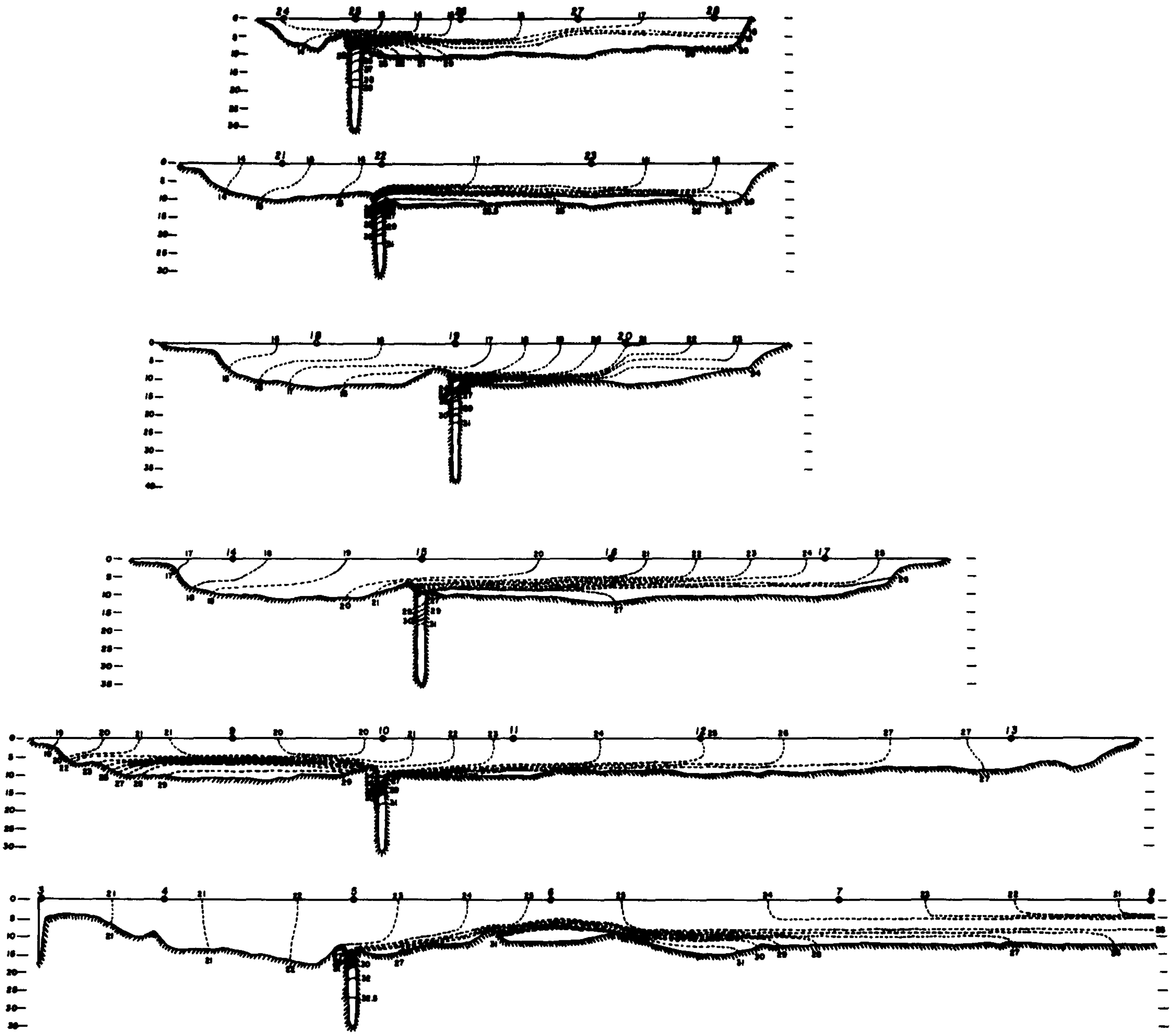
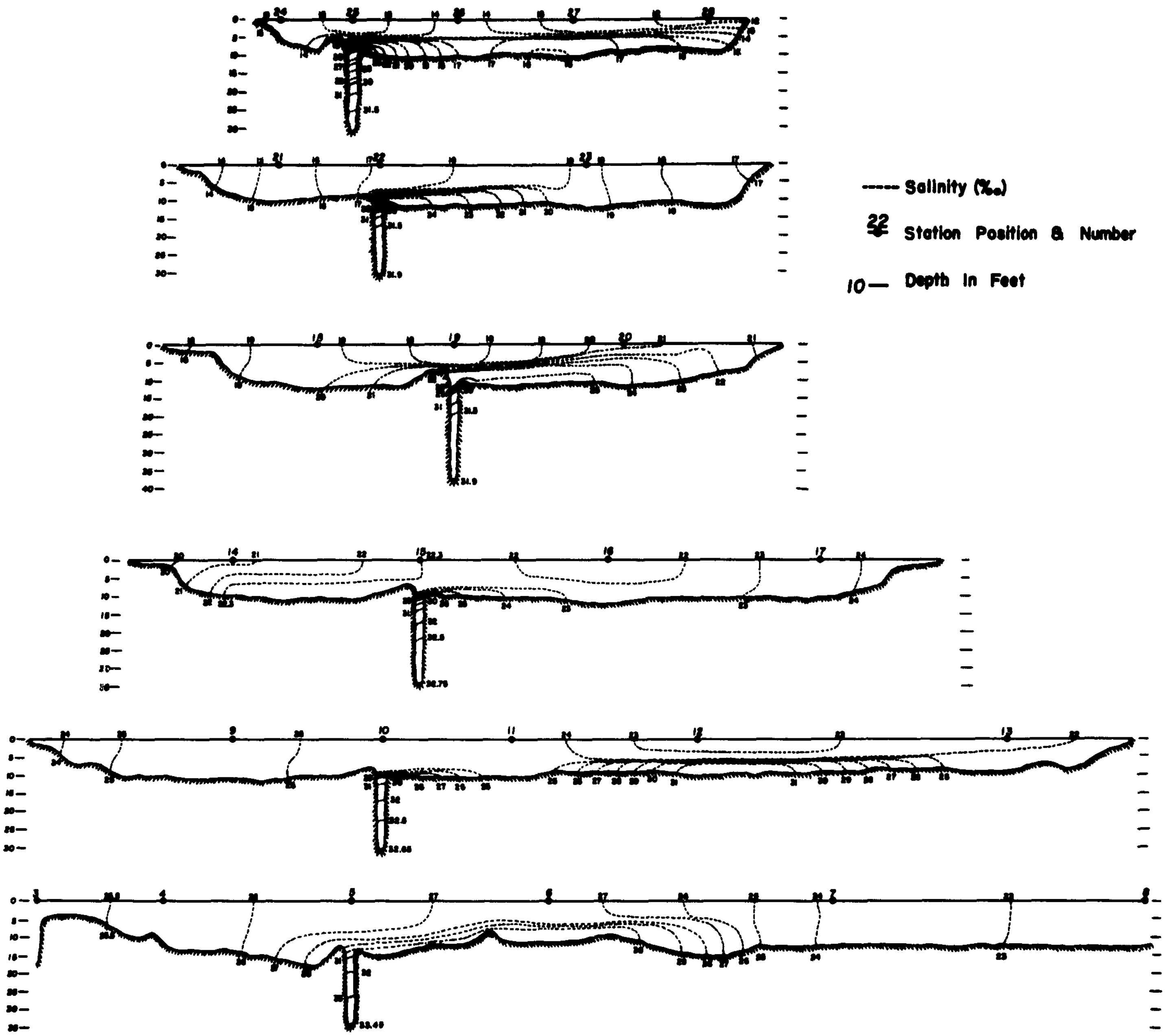


FIGURE V



SALINITY-DEPTH SECTIONS
(Ebb Tide)
Mobile Bay, Alabama
October 1952

FIGURE VI



SALINITY-DEPTH SECTIONS
(Flood Tide)
Mobile Bay, Alabama
October 1962

FIGURE VIa.

SALINITY-DEPTH SECTION, LOWER MOBILE BAY SHIP CHANNEL

EBB TIDE

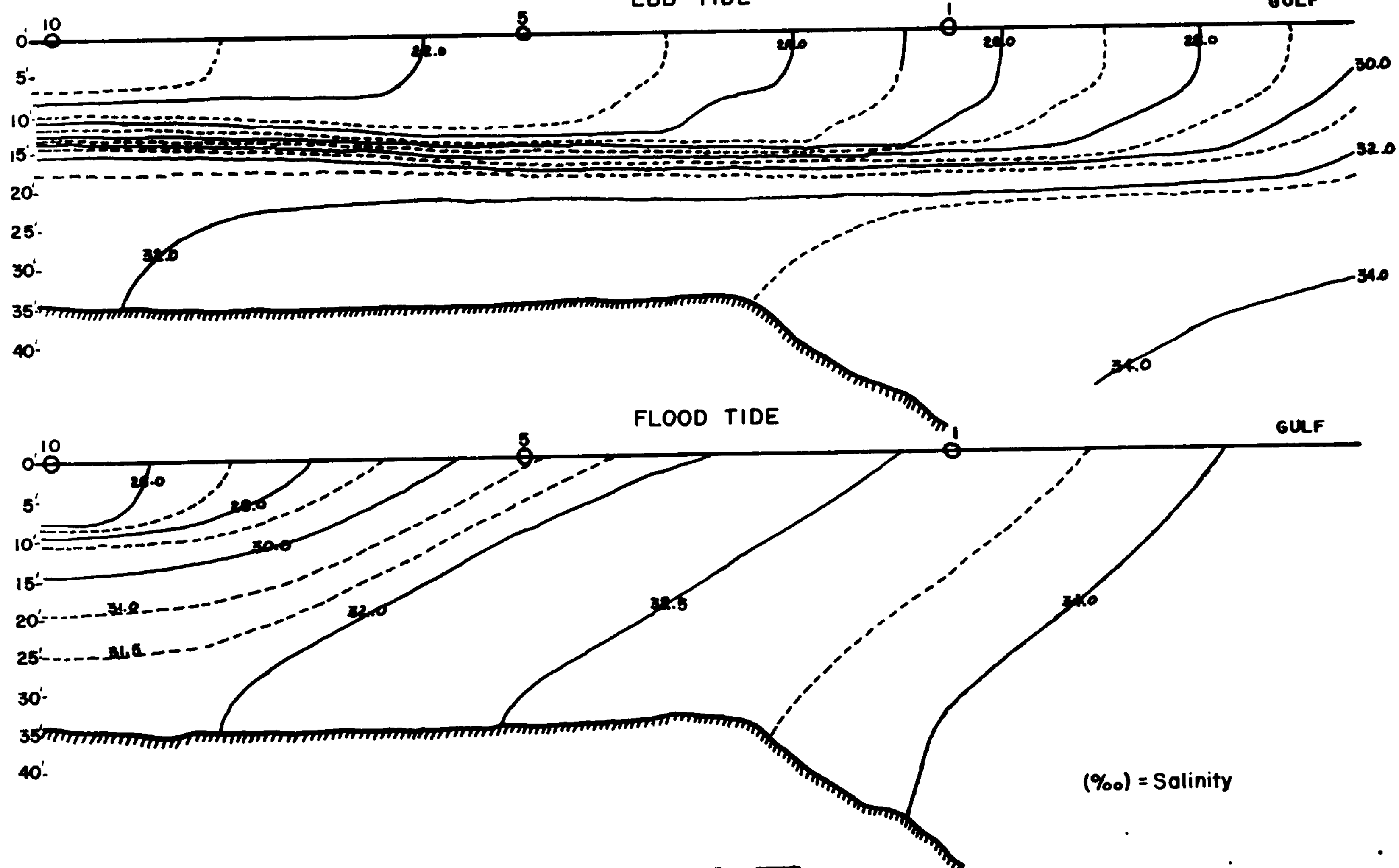


FIGURE VII

T-S DIAGRAMS of MOBILE BAY, ALABAMA

OCTOBER, 1952

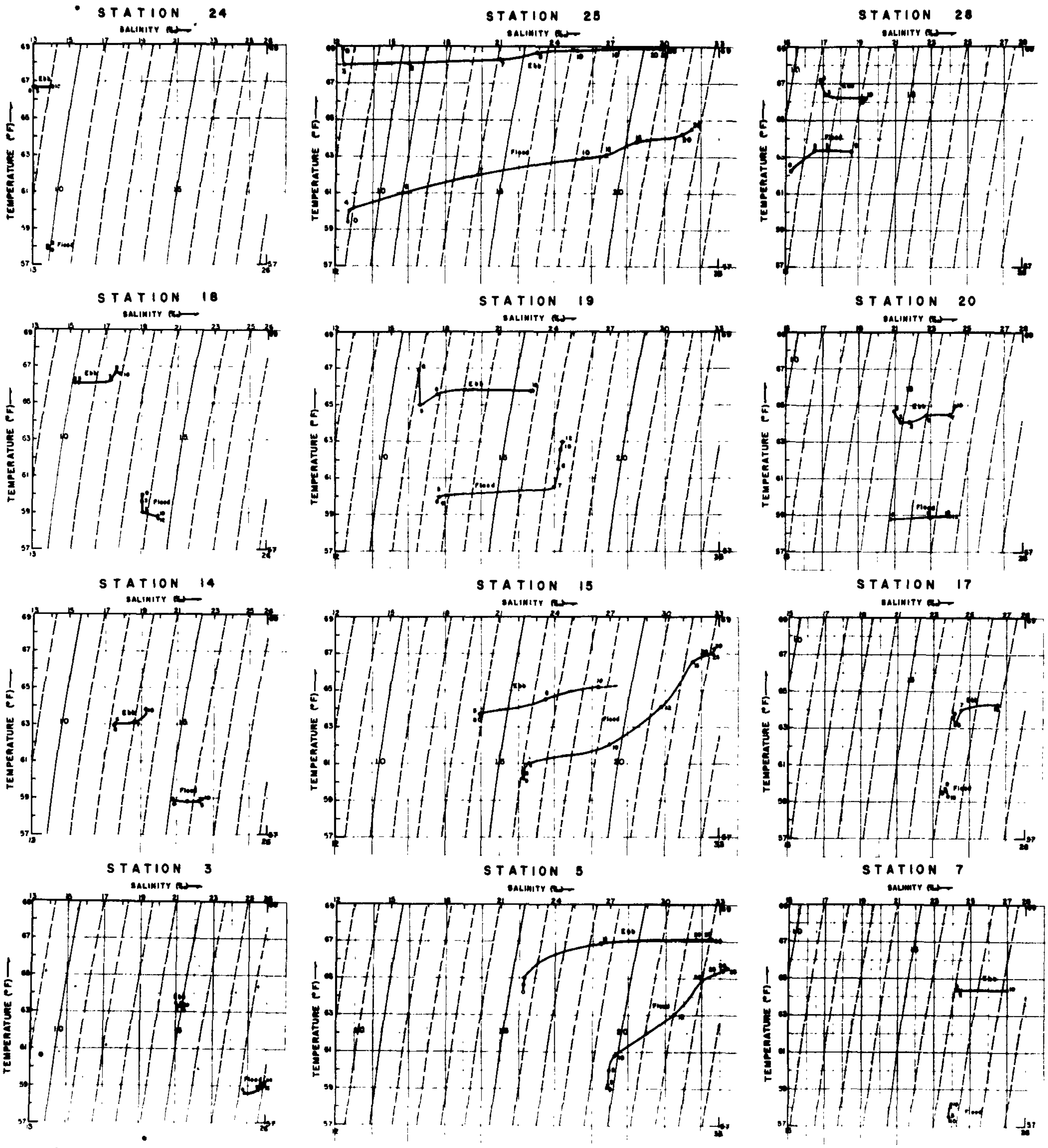


FIGURE VIII

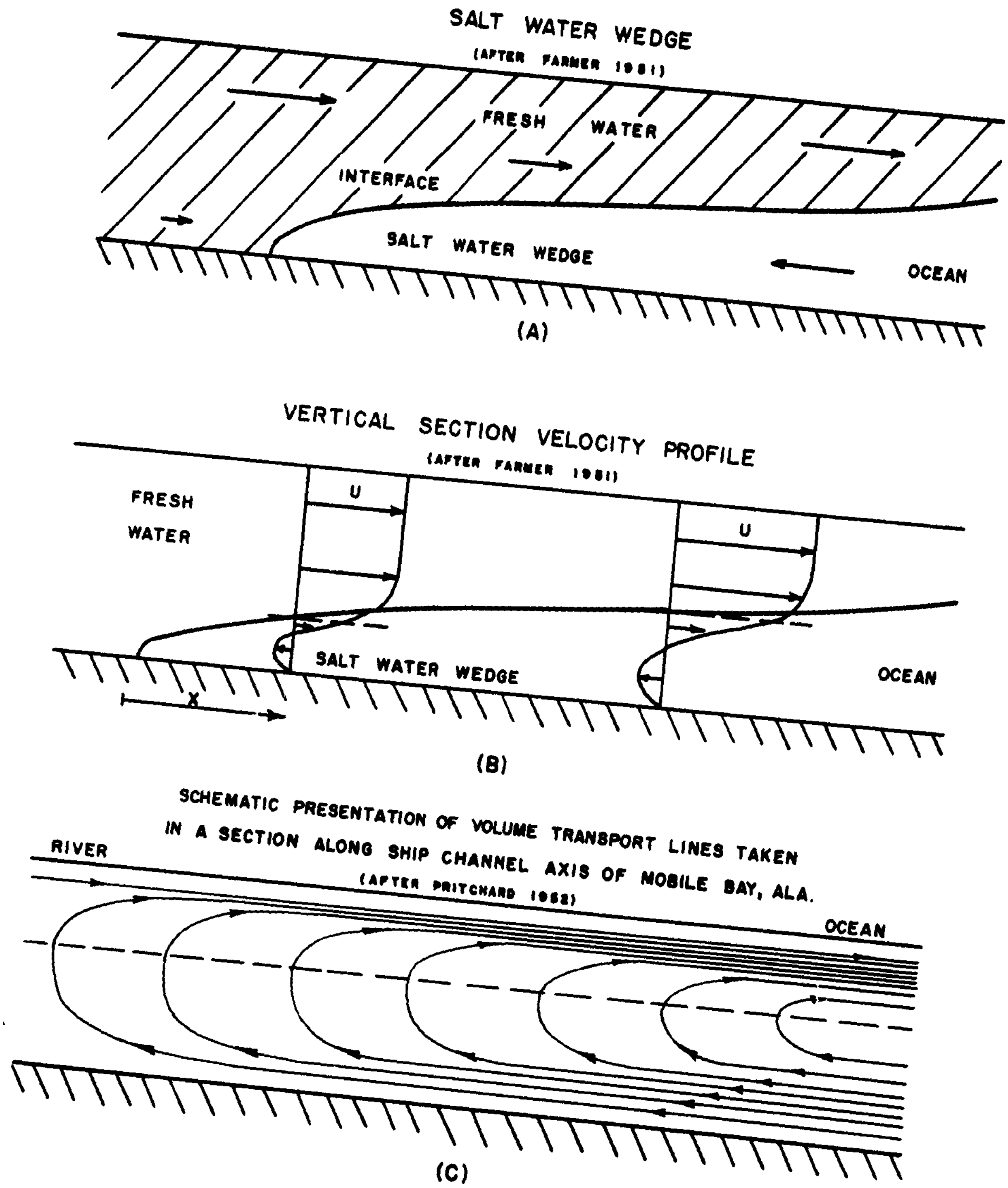

SALT WATER WEDGE
(AFTER FARMER 1951)
FRESH WATER
INTERFACE
SALT WATER WEDGE
OCEAN
(A)
VERTICAL SECTION VELOCITY PROFILE
(AFTER FARMER 1951)
FRESH WATER
U
U
SALT WATER WEDGE
OCEAN
X
(B)
SCHEMATIC PRESENTATION OF VOLUME TRANSPORT LINES TAKEN
IN A SECTION ALONG SHIP CHANNEL AXIS OF MOBILE BAY, ALA.
(AFTER PRITCHARD 1952)
RIVER
OCEAN
(C)

FIGURE IX

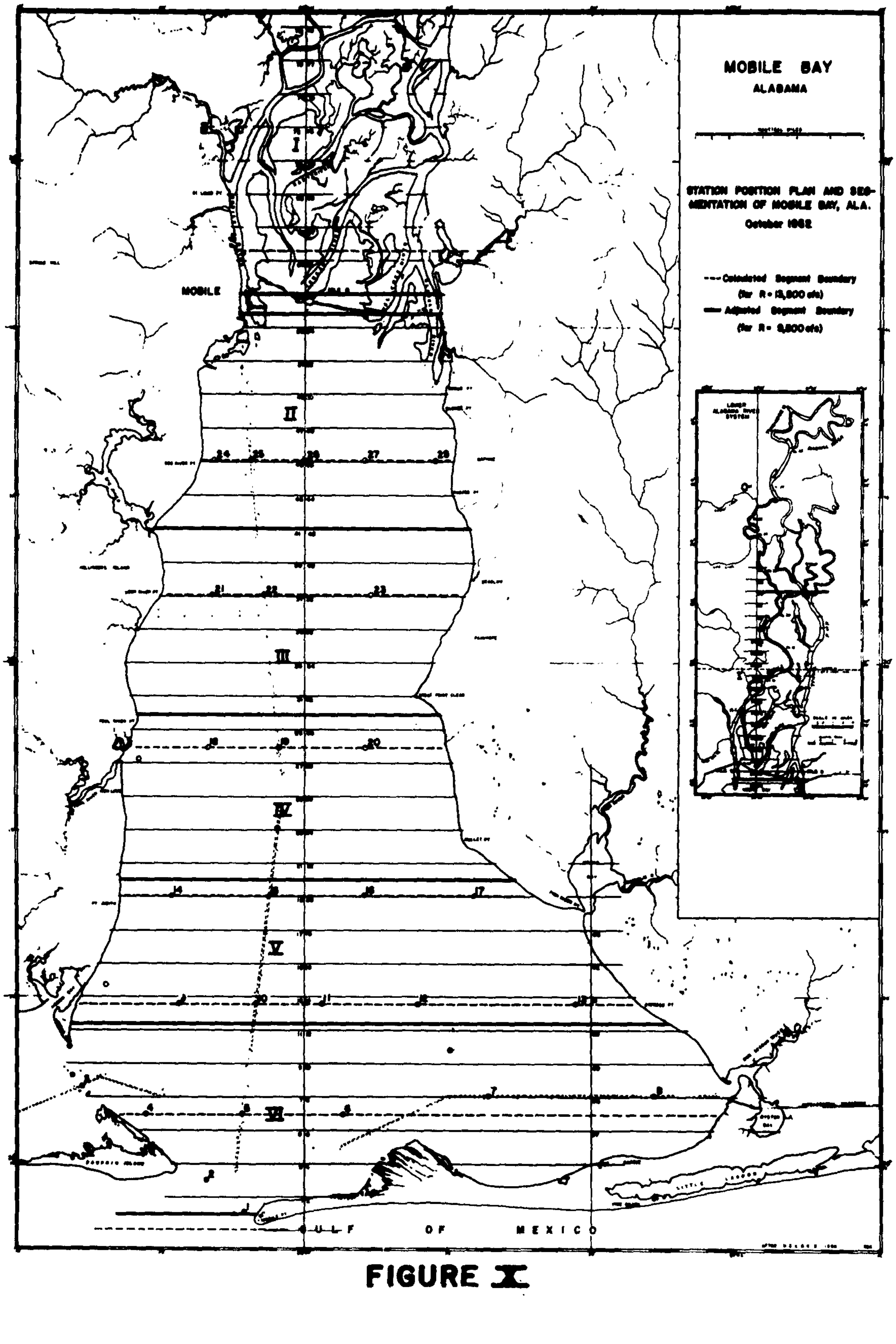

MOBILE BAY
ALABAMA
STATION POSITION PLAN AND SEGMENTATION OF MOBILE BAY, ALA.
October 1962
Calculated Segment Boundary
Adjusted Segment Boundary
MOBILE
GULF OF MEXICO

FIGURE X

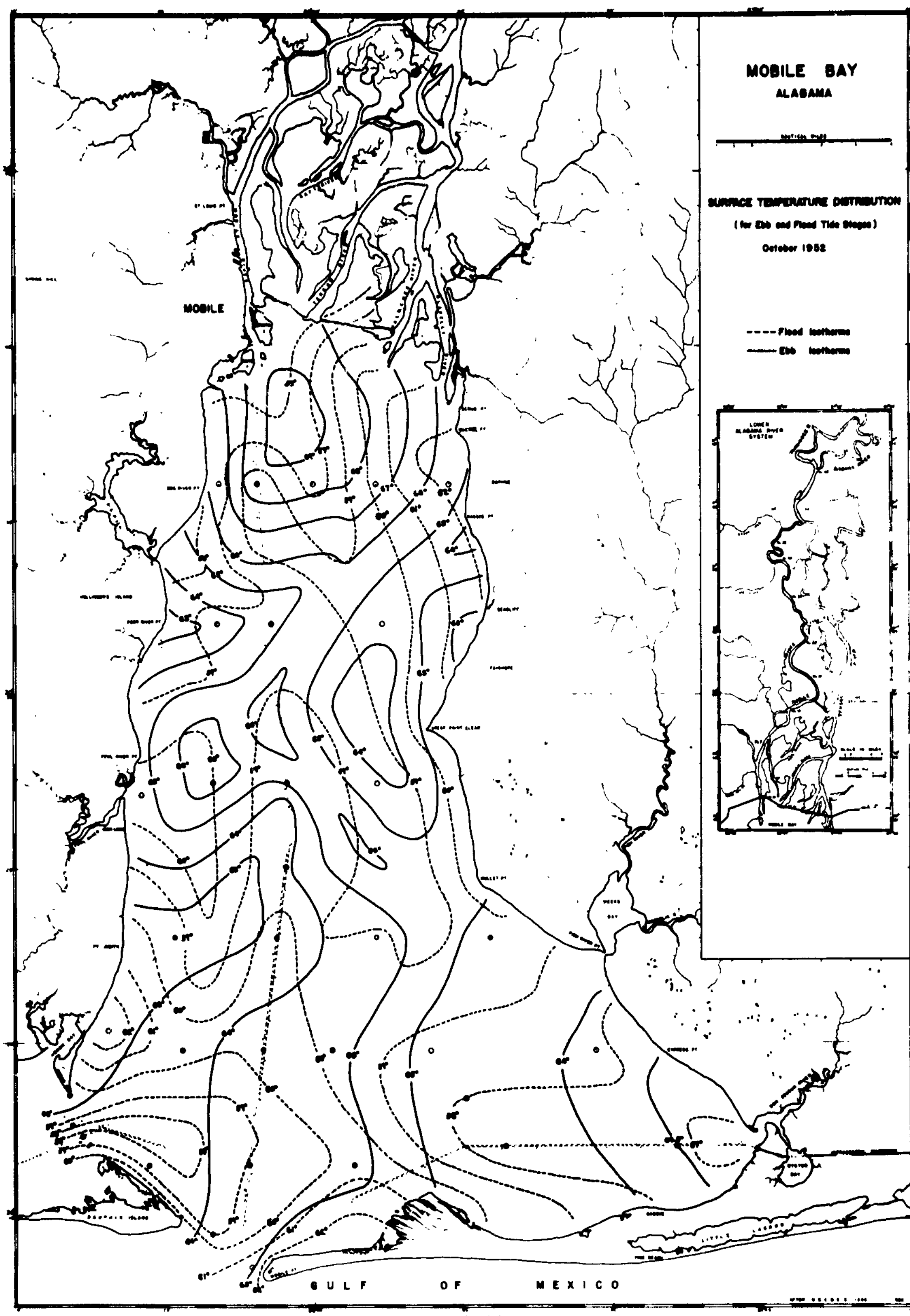

MOBILE BAY
ALABAMA
SURFACE TEMPERATURE DISTRIBUTION
(for Ebb and Flood Tide Stages)
October 1952
Flood Isotherms
Ebb Isotherms
LOWER ALABAMA RIVER SYSTEM
MOBILE
GULF OF MEXICO

FIGURE XI

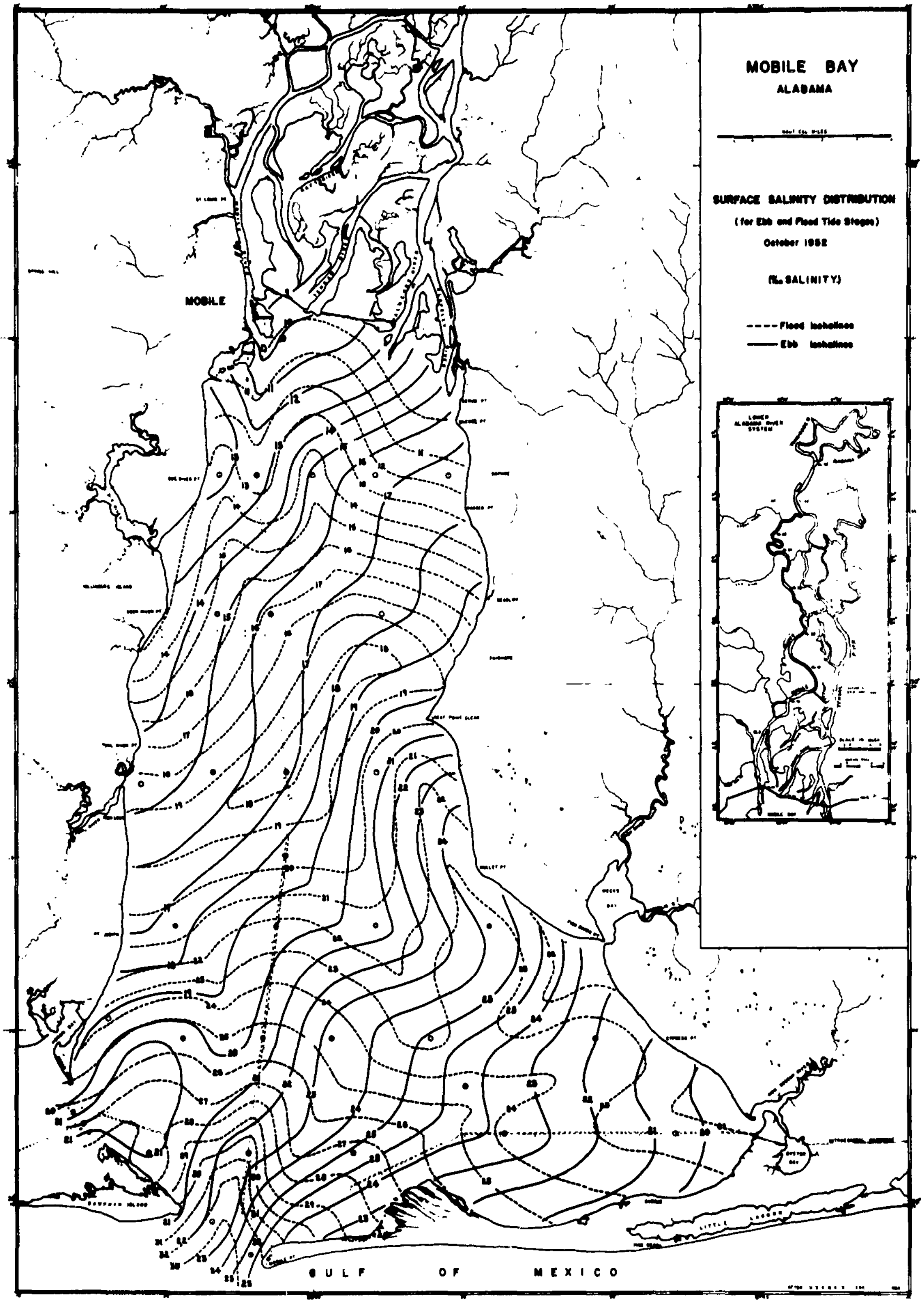
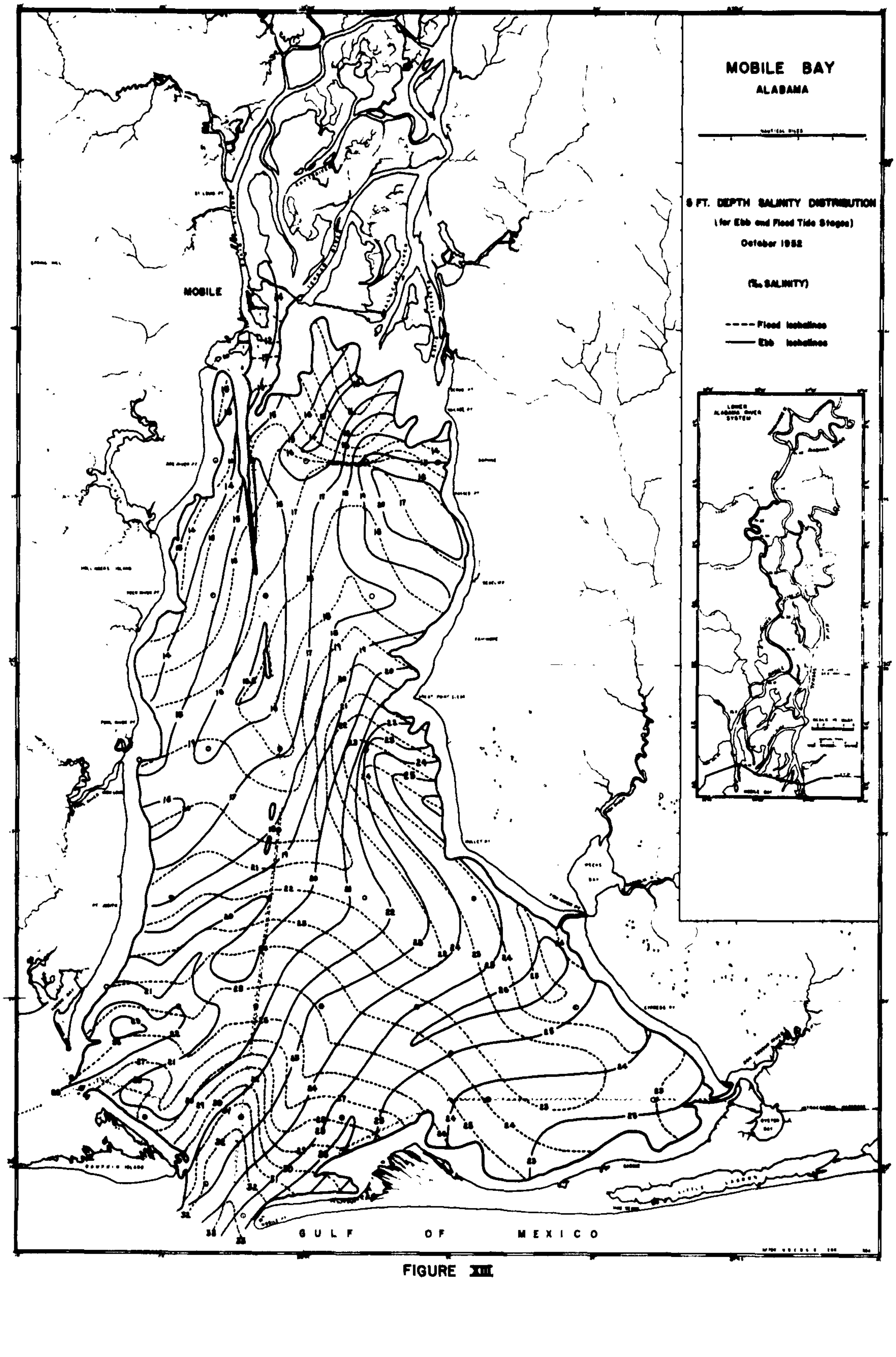

MOBILE BAY
ALABAMA
SURFACE SALINITY DISTRIBUTION
(for Ebb and Flood Tide Stages)
October 1952
(‰ SALINITY)
----- Flood Isohalines
——— Ebb Isohalines
MOBILE
GULF OF MEXICO

FIGURE XII



MOBILE BAY
ALABAMA
5 FT. DEPTH SALINITY DISTRIBUTION
(for Ebb and Flood Tide Stages)
October 1952
(‰ SALINITY)
Flood Isohalines
Ebb Isohalines
MOBILE
GULF OF MEXICO

FIGURE XIII

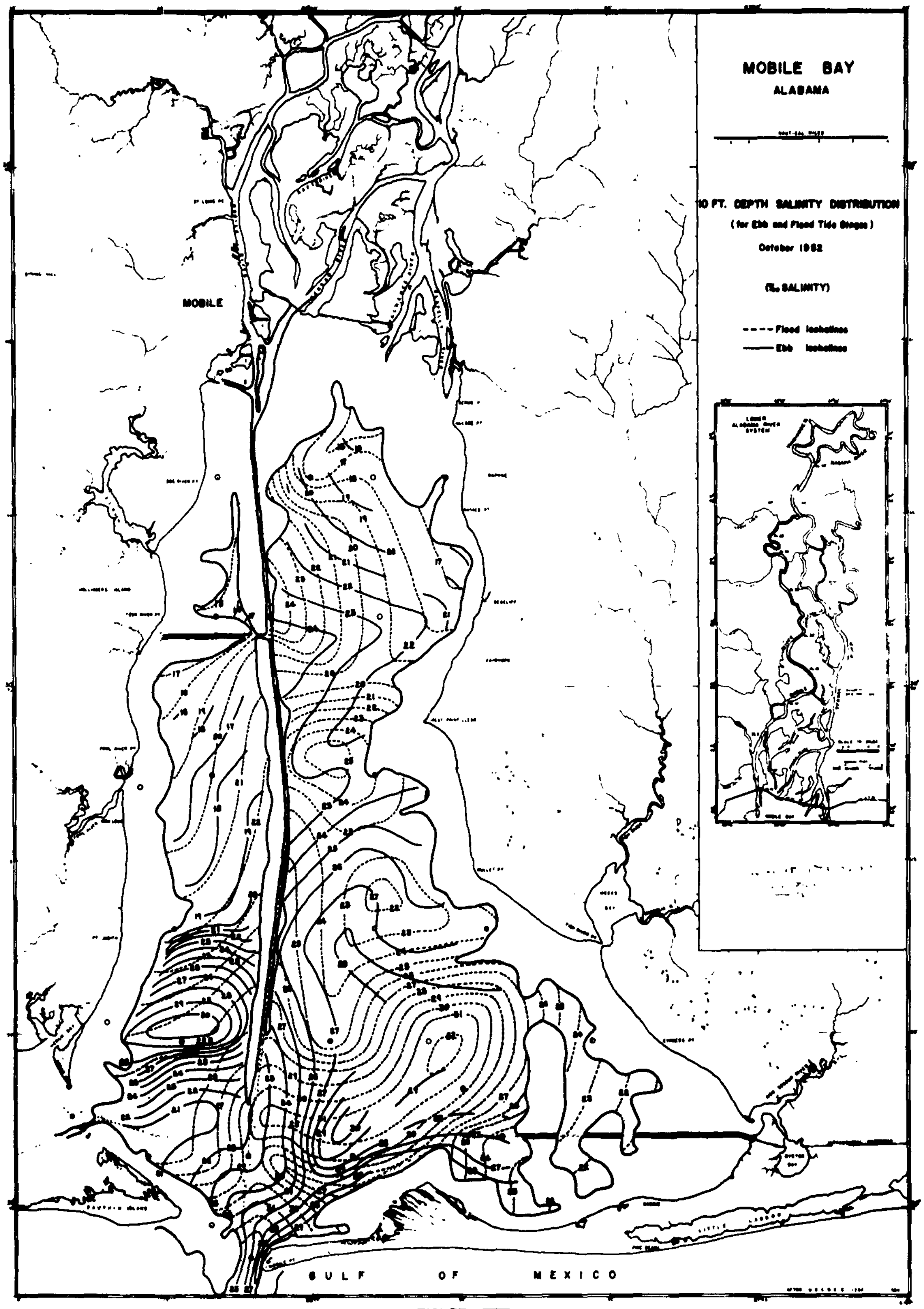

MOBILE BAY
ALABAMA
10 FT. DEPTH SALINITY DISTRIBUTION
(for Ebb and Flood Tide Stages)
October 1952
(‰ SALINITY)
Flood Isohalines
Ebb Isohalines
MOBILE
GULF OF MEXICO

FIGURE XIV

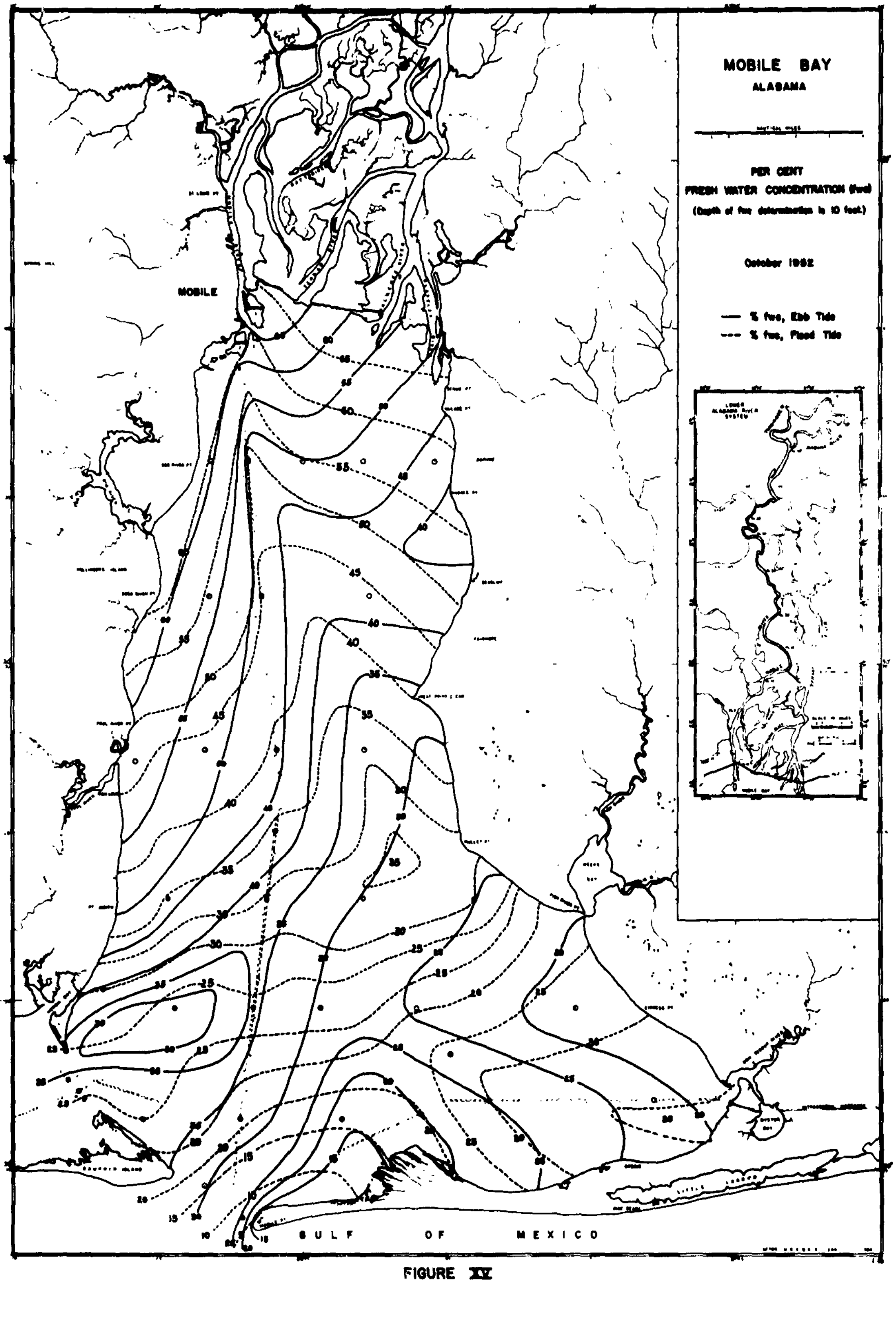

MOBILE BAY
ALABAMA
PER CENT
FRESH WATER CONCENTRATION (fwc)
(Depth of fwc determination is 10 feet)
October 1962
% fwc, Ebb Tide
% fwc, Flood Tide
MOBILE
GULF OF MEXICO

FIGURE XV

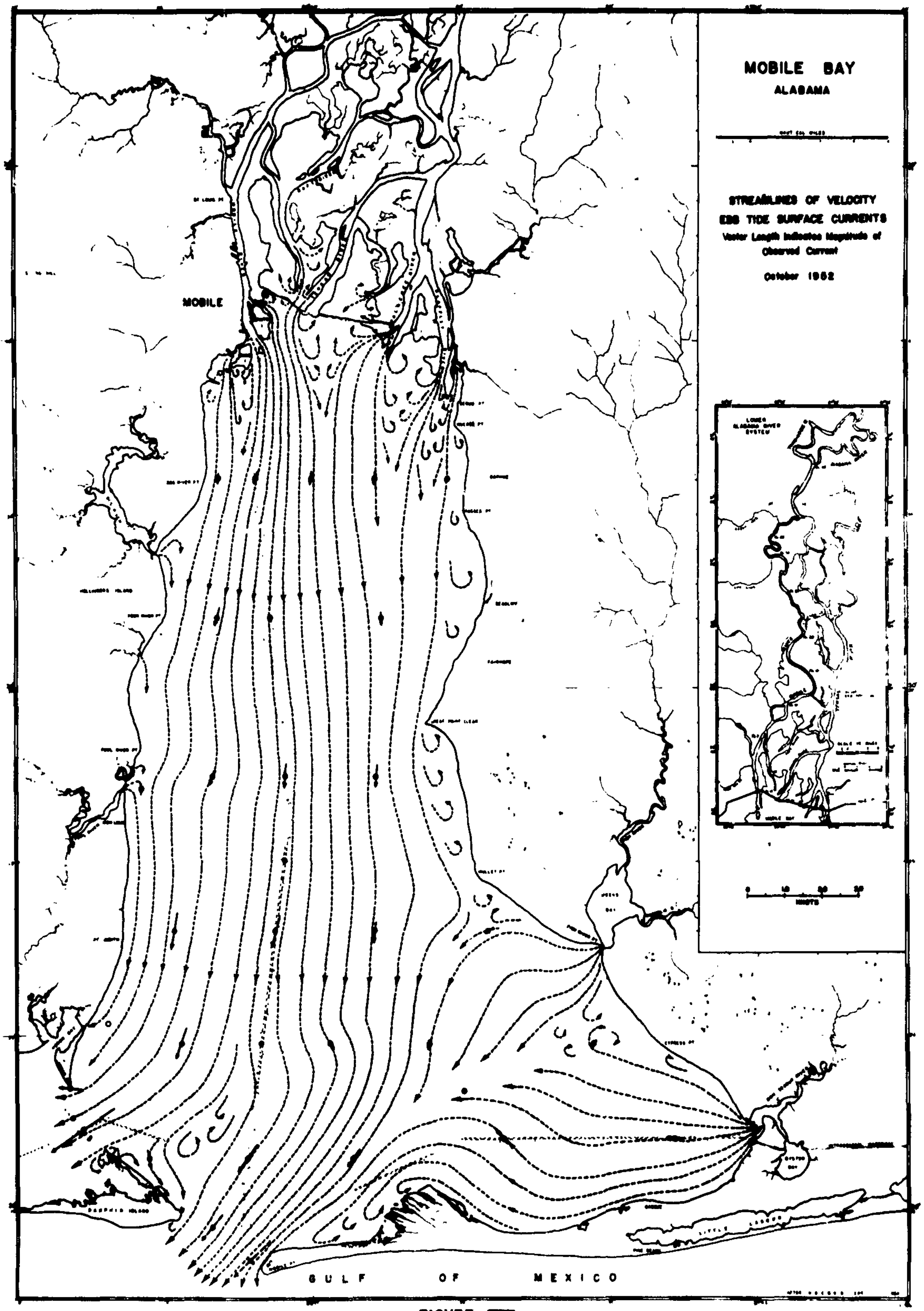
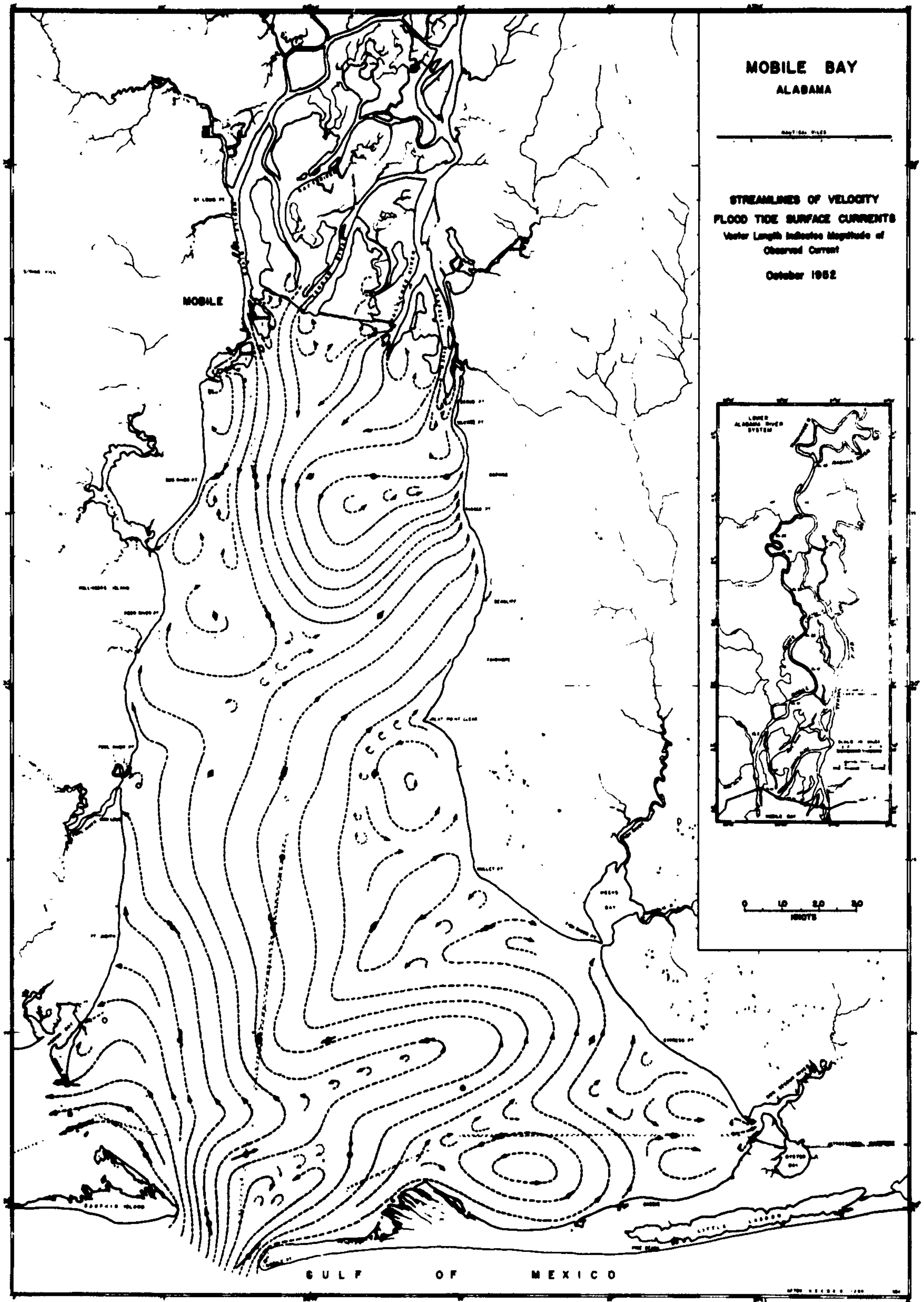

MOBILE BAY
ALABAMA
STREAMLINES OF VELOCITY
EBB TIDE SURFACE CURRENTS
Vector Length Indicates Magnitude of
Observed Current
October 1952
MOBILE
GULF OF MEXICO

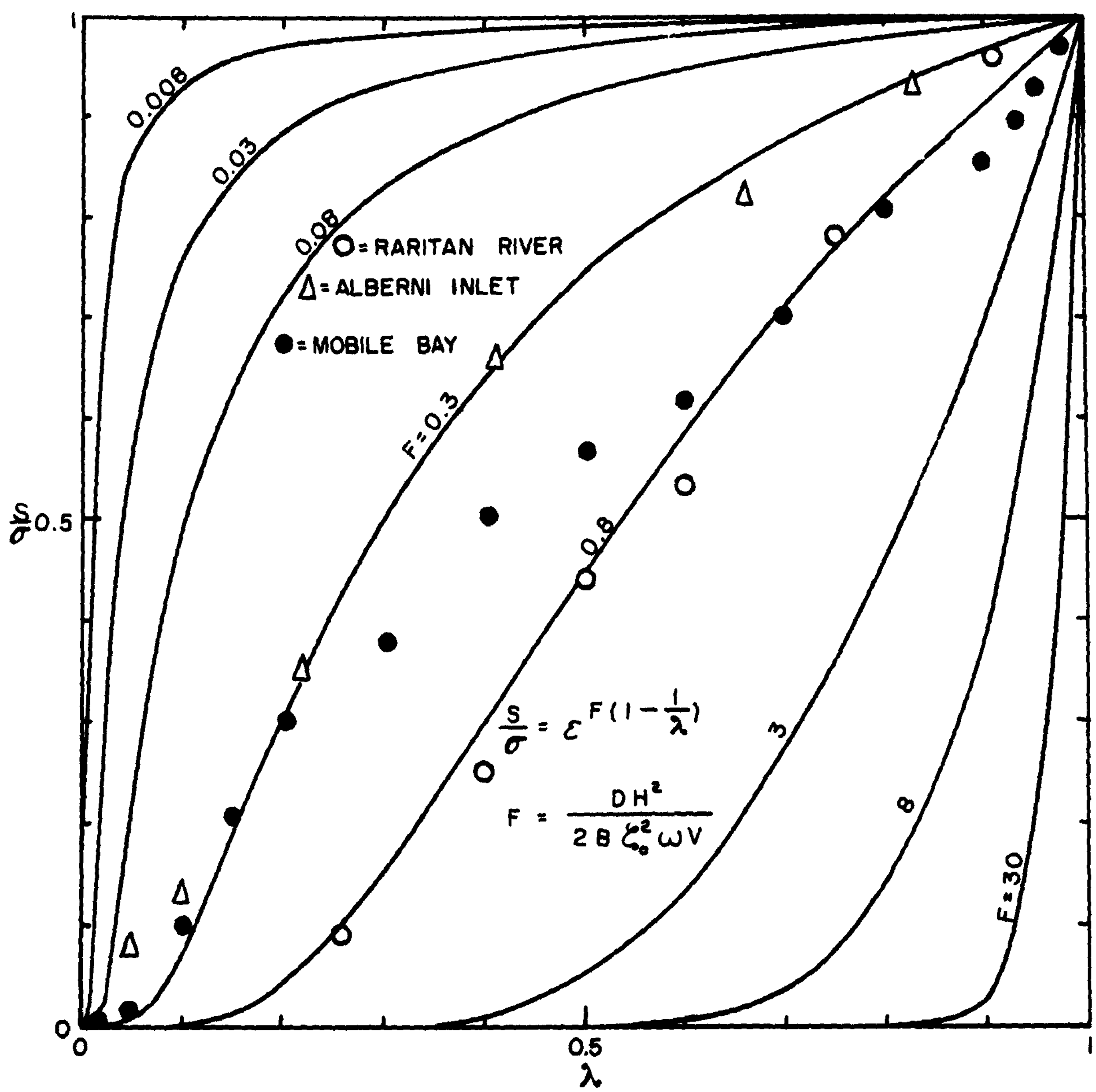
FIGURE XVI



MOBILE BAY
ALABAMA
STREAMLINES OF VELOCITY
FLOOD TIDE SURFACE CURRENTS
Vector Length Indicates Magnitude of Observed Current
October 1952
MOBILE
GULF OF MEXICO

FIGURE XVII

FLUSHING NUMBER (F) DIAGRAM FOR THREE ESTUARIES



(After Stommel, H. 1950)

FIGURE XVIII

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